

Transverse Spin Asymmetries at



Anselm Vossen



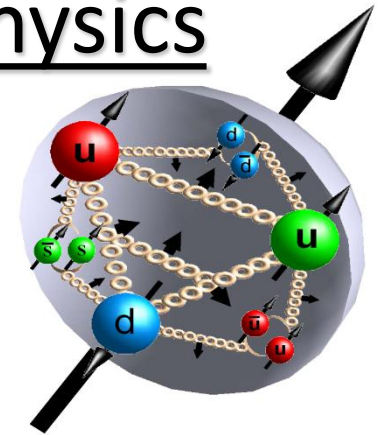
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Motivation for Transverse Spin Physics



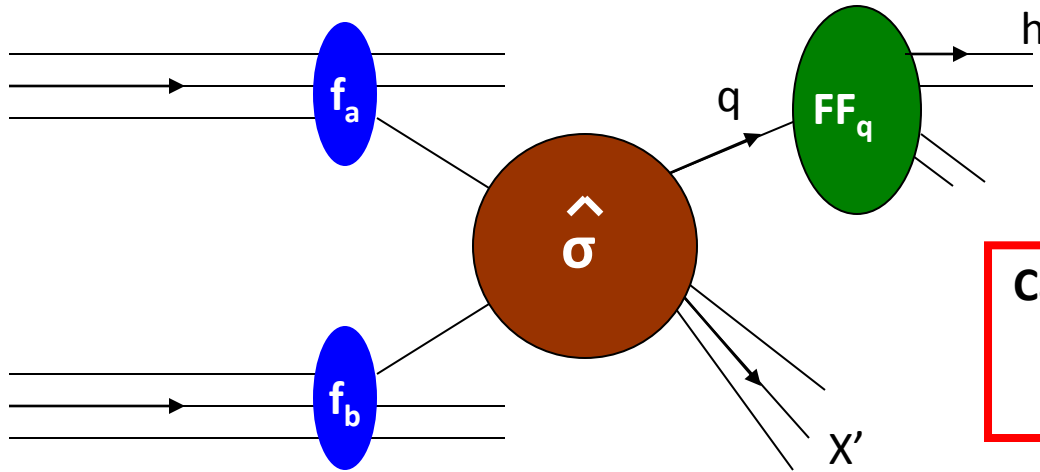
- What contributes most of the visible mass in the universe?

– *Not Higgs:
The QCD interaction!*

- SPIN is fundamental quantity:
What role does it play in strong interactions?

- ➔ Interesting transverse spin effects help us understand QCD
- ➔ Transverse Spin allows to probe Matrix elements via Interference
- ➔ RHIC is the only place with polarized proton collisions in the foreseeable future
- ➔ Test Factorization
- ➔ Explore role of soft interactions
- ➔ Access (local) P violating effects
- ➔ Similar effects could maybe be observed in HI collisions to test polarization of quarks

Origin of Single Spin Asymmetries



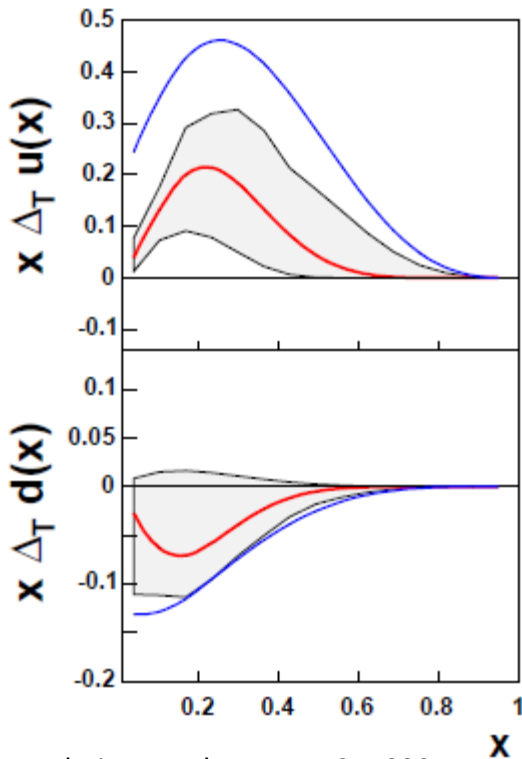
Can initial and/or final state effects generate large transverse spin asymmetries? ($A_N \sim 10^{-1}$)

$$\frac{d^3 \sigma^\uparrow(pp^\uparrow \rightarrow \pi^+ X)}{dx_1 dx_2 dz} \propto \underbrace{q_i^\uparrow(x_1, k_{q,T}) \cdot G(x_2)}_{\text{Proton Structure}} \times \underbrace{\frac{d^3 \hat{\sigma}^\uparrow(q_i q_j \rightarrow q_k q_l)}{dx_1 dx_2}}_{\text{pQCD, small spin dependence}} \times \underbrace{FF_{q_{k,l}}(z, p_{h,T})}_{\text{fragmentation function}}$$

Transverse Spin Structure Functions

Transversity

$$\delta q(x) = q_{\uparrow}^{\uparrow}(x) - q_{\uparrow}^{\downarrow}(x)$$



Anselmino et. al., PRD75 054032

correlation between transverse
proton spin and quark spin

$S_p - S_q$ coupling

$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^\perp(z_2, \bar{k}_\perp^2)}_{\text{Collins FF}}$$

Quark transverse
spin distribution

Collins FF

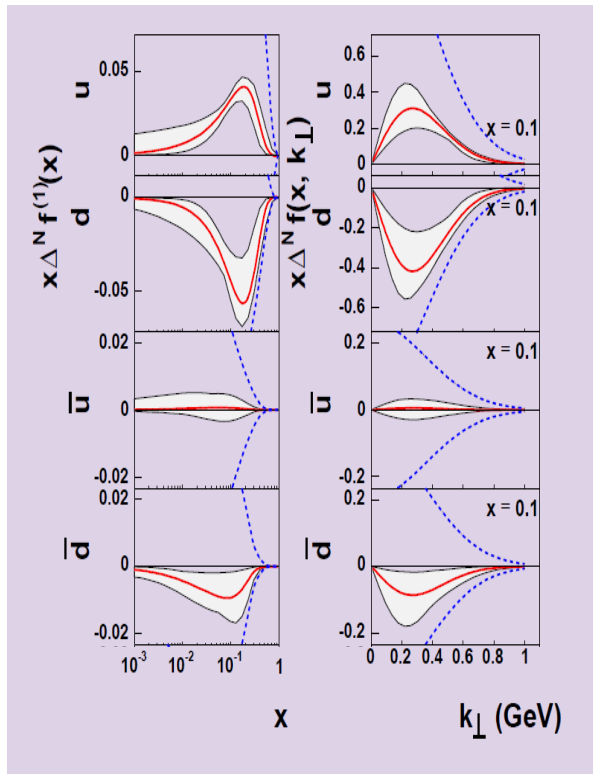
J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

- One of three collinear parton distribution functions needed to describe the spin structure of the nucleon at leading order
- Chiral odd quantity: needs chiral odd partner \rightarrow FF
- Inaccessible in inclusive measurements: poorly known



Transverse Spin Structure Functions

Sivers distribution:



correlation between transverse proton spin and quark/gluon transverse momentum

$S_p - k_T$ coupling (L_q ?)

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$

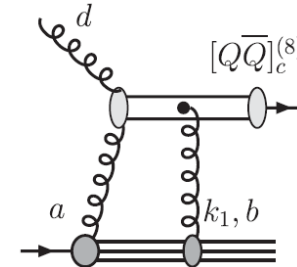
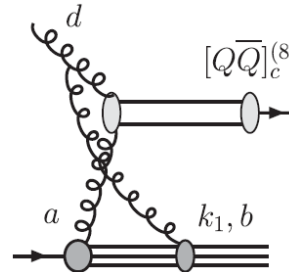
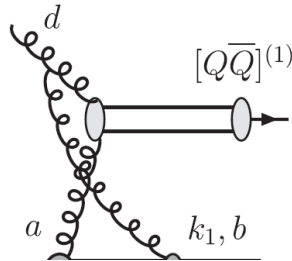
Sivers distribution

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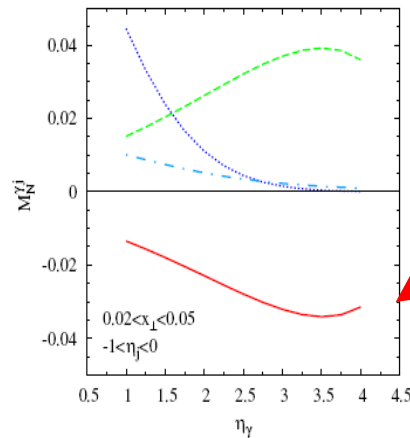
D. Sivers, Phys. Rev. D **41**, 83 (1990)⁵

- Access to non-collinear parton distribution functions
- Needs orbital angular momentum of the quarks

'Soft' transverse momentum breaks factorization



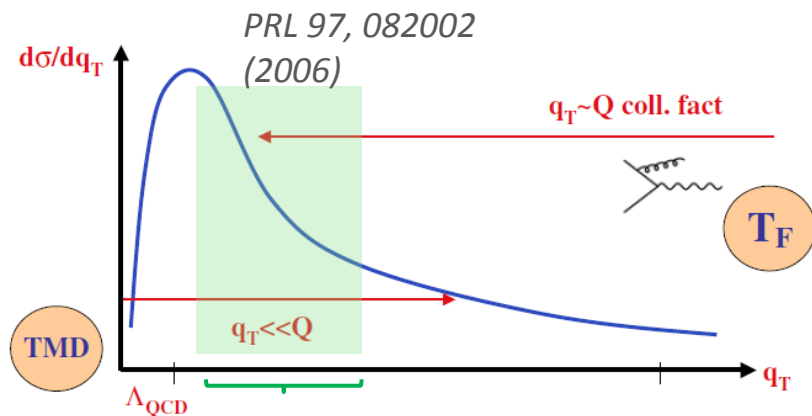
Weighted
moment of
 A_N photon+jet



no process
dependence

correct
process
dependence

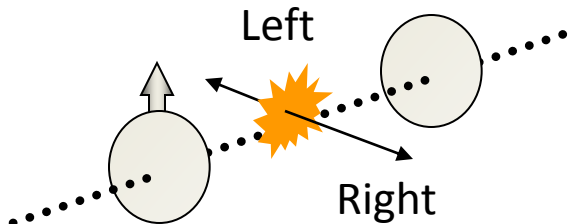
- Color 'entanglement' is predicted to lead to process dependence
- Size of effect unclear



- At high scales collinear higher Twist approach suggested
- Characteristic $1/p_T$ dependence not yet observed

$$T_{q,F}, T_G^{(f)}$$

A simple observable: Left-Right Asymmetries



$$A_N = \frac{1}{P} \frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

A_N difference in cross-section between particles produced to the left and right

Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$

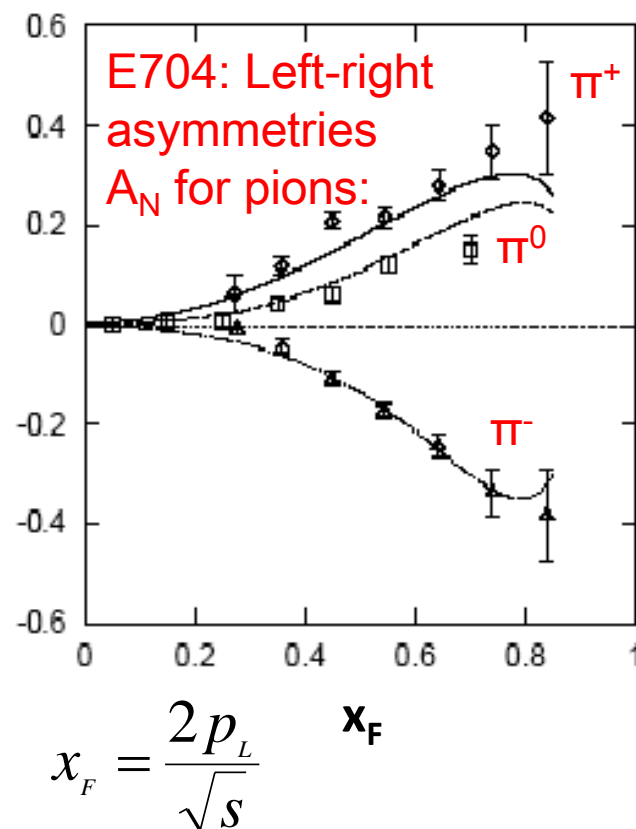
$$\sqrt{s} = 20 \text{ GeV}$$

A_N $O(10^{-1})$ Measured

A_N

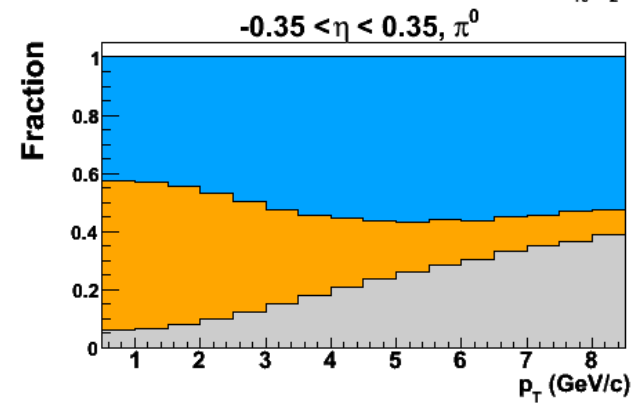
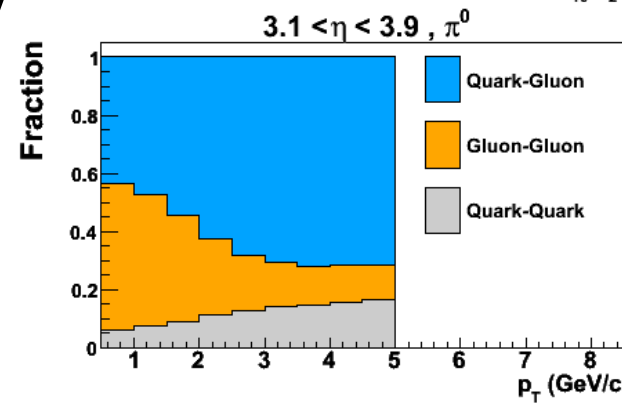
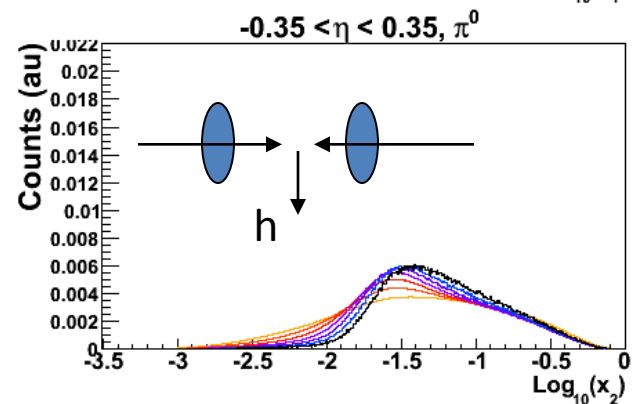
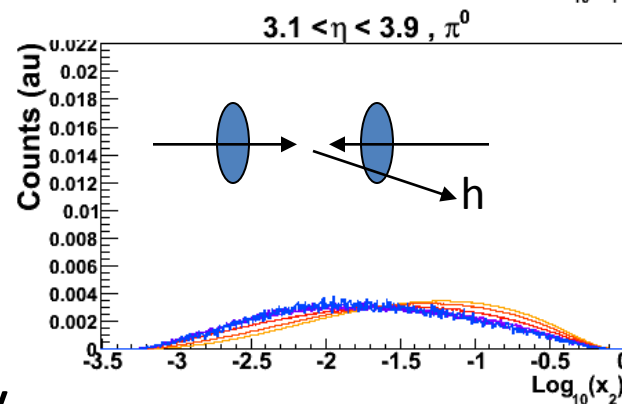
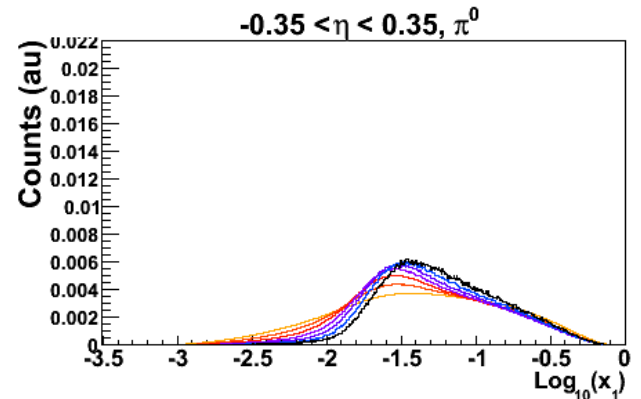
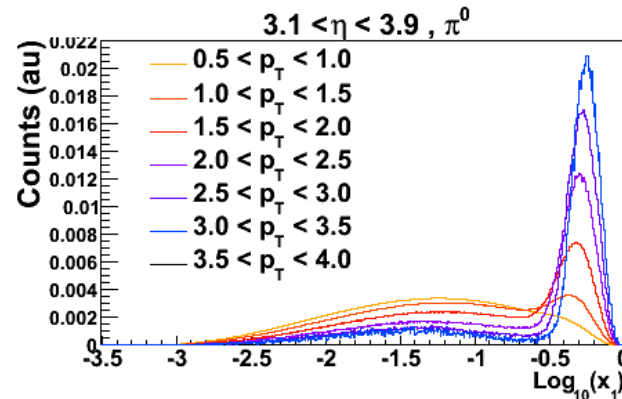
RHIC first time in perturbative regime

So far A_N is only sizable asymmetry measured with high precision

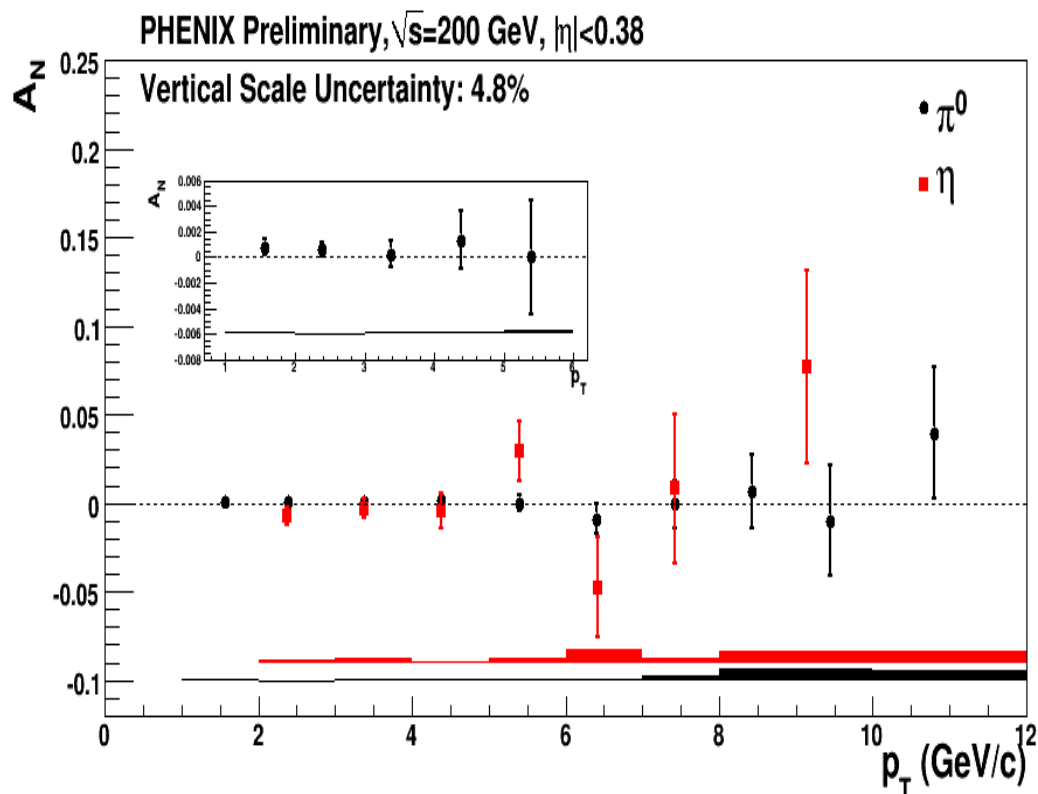


Ψ Only scattering at forward angles probes valence quark distributions

- Estimated with Pythia simulation package
- Mid-rapidity:
Low p_T dominated by gluon gluon scattering
- Forward-rapidity
High- x + Low- x scattering



Mid-rapidity π^0 and η A_N

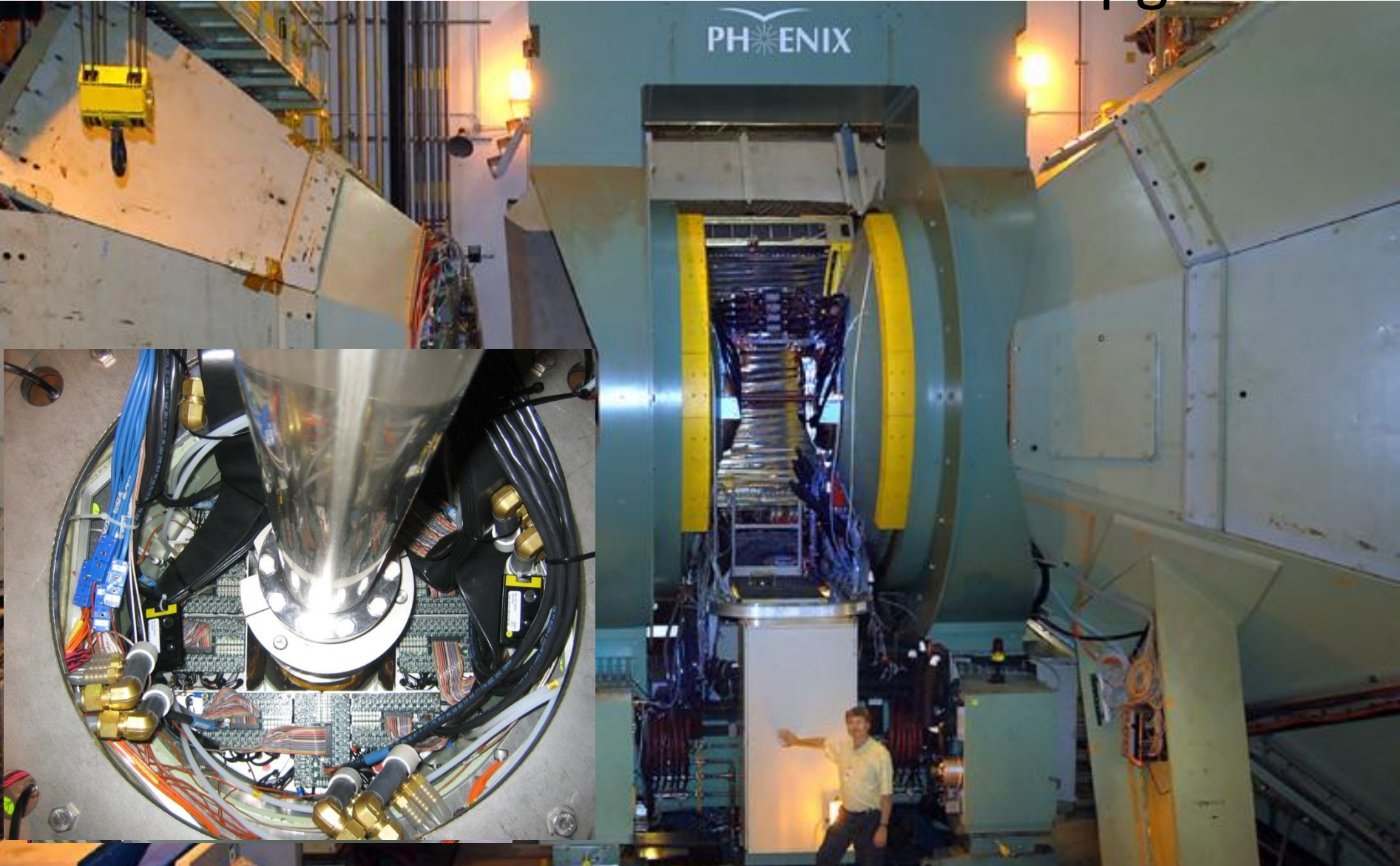


- Constrains gluon Sivers
 - But hint of: J/Psi asymmetries
 - ->Ming Liu's talk
- Transverse spin asymmetries are valence quark effects
 - Only strong in forward direction
 - Motivation for MPC (this talk)
 - PHENIX forward upgrade (Christine Aidala's talk)

- So we have to look in the forward direction to observe significant asymmetries



PHENIX Muon Piston Calorimeter Upgrade



Small cylindrical hole in Muon Magnet Piston, Radius 22.5 cm and Depth 43.1 cm

Measuring π^0 's with the MPC

Clustering:

1. Groups towers together above an energy threshold
2. Fit energy and position of incident photon

If two photons are separated by ~ 1 tower, they are reconstructed as a single cluster.

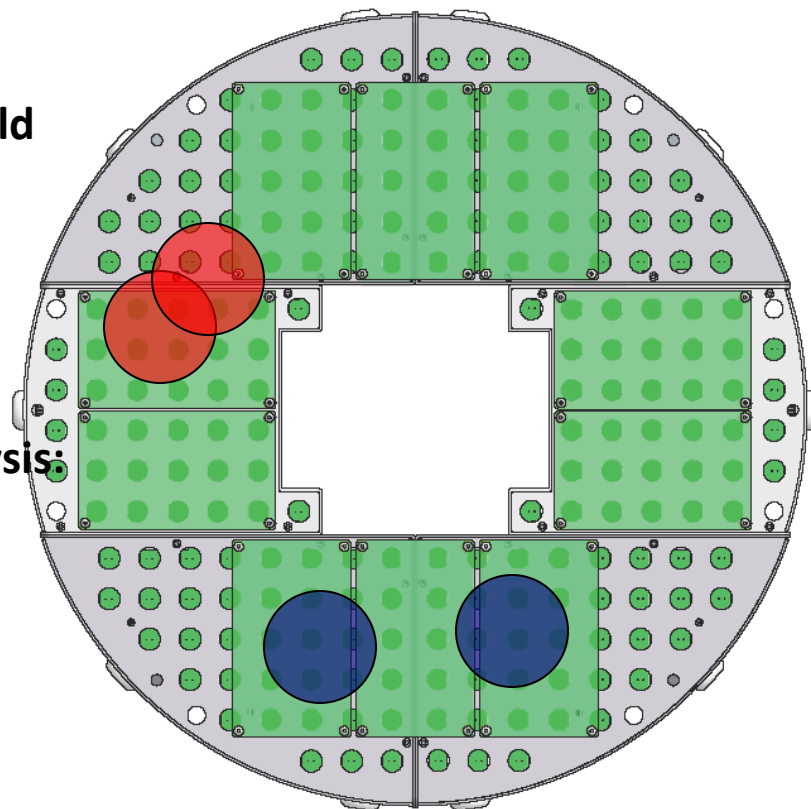
Physics Impact:

Photon merging effects prevent two-photon π^0 analysis;
for $E_{\pi^0} > 20$ GeV ($p_T > 2$ GeV/c)

- At $\sqrt{s} = 62$ GeV
20 GeV $\rightarrow 0.65 x_F$: Two-photon π^0 analysis
- At $\sqrt{s} = 200$ GeV
20 GeV $\rightarrow 0.20 x_F$ for two-photon π^0 analysis

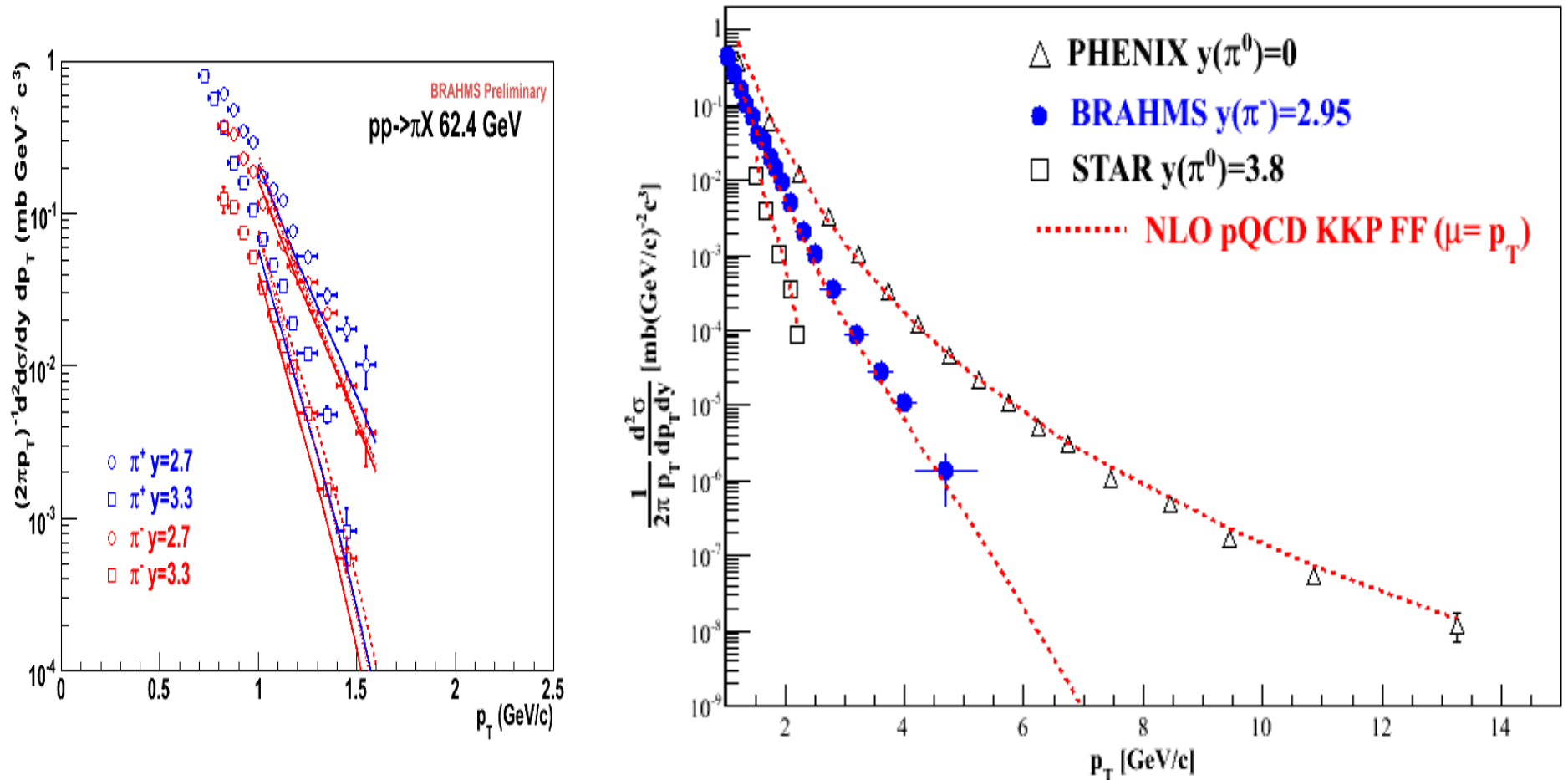
Use merged Single clusters as proxy for π^0

Yields dominated by π^0 's but subject to backgrounds



Decay photon impact positions for **low** and **high** energy π^0 's

NLO pQCD FWD π^0 Cross-section

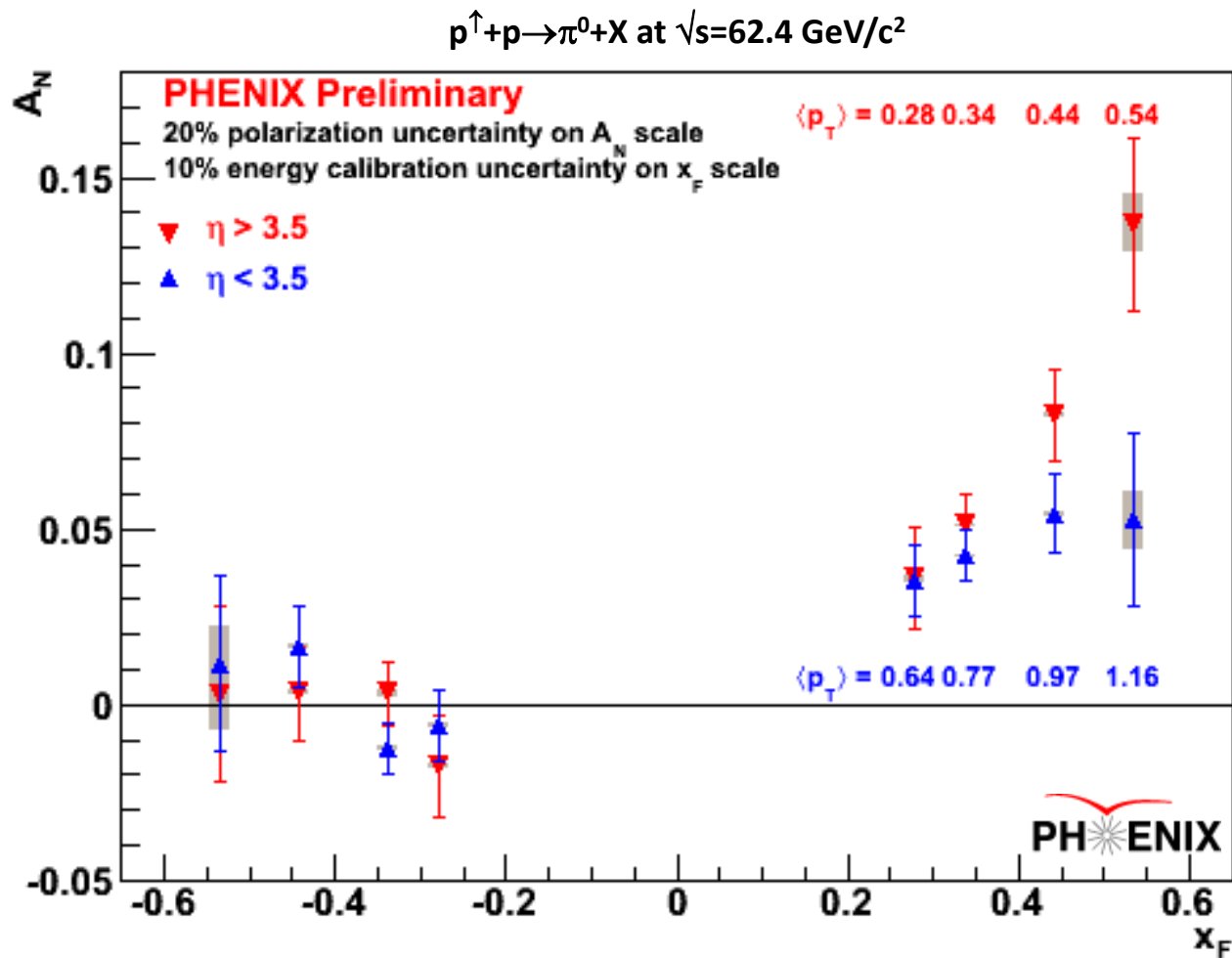


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- Cross-sections generally better described at mid-rapidity and at higher \sqrt{s}
- NLL calculations are very promising for intermediate to lower \sqrt{s}
 - PHENIX $\sqrt{s}=62.4$ GeV $y=0$ π^0 cross-section, arXiv:0810.0701
- More remarkable that $A_N(x_F)$ are qualitatively similar across all \sqrt{s}

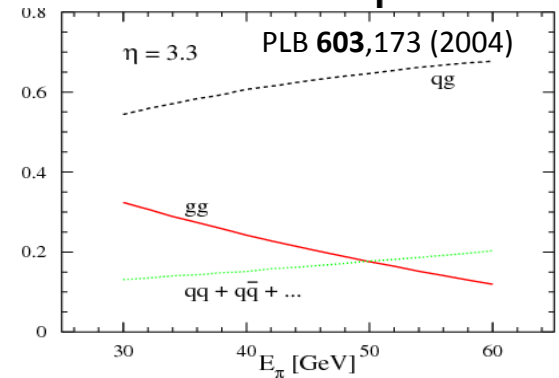
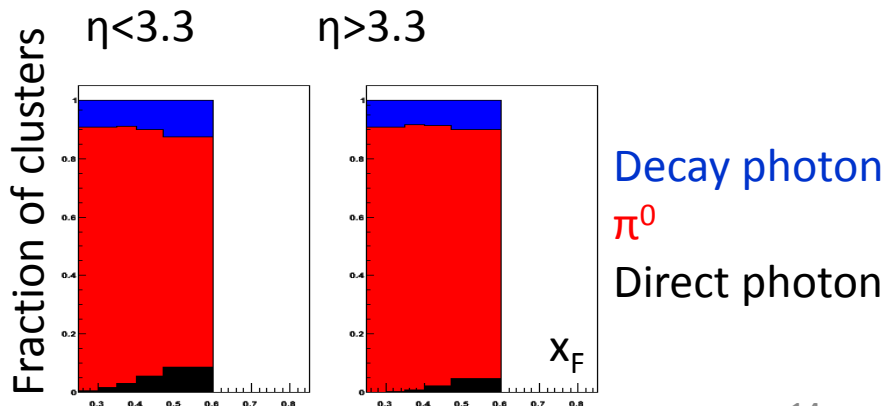
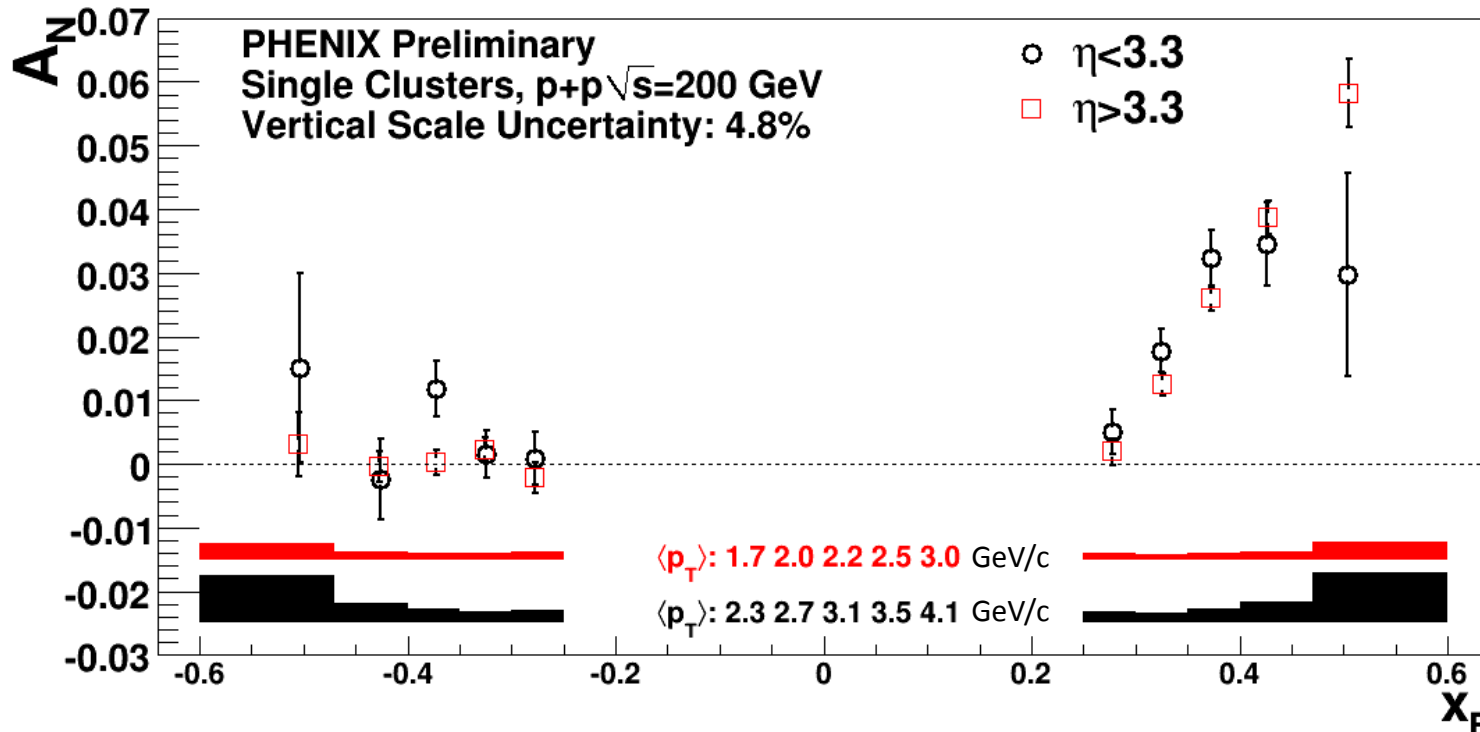
Ψ

$\pi^0 A_N$ at High x_F , $\sqrt{s}=62.4$ GeV



- Large asymmetries at forward x_F
 - Valence quark effect?
- x_F , p_T , \sqrt{s} , and η dependence provide quantitative tests for theories
- Complementary to other data, ie, Brahm's π^\pm , which allows flavor study

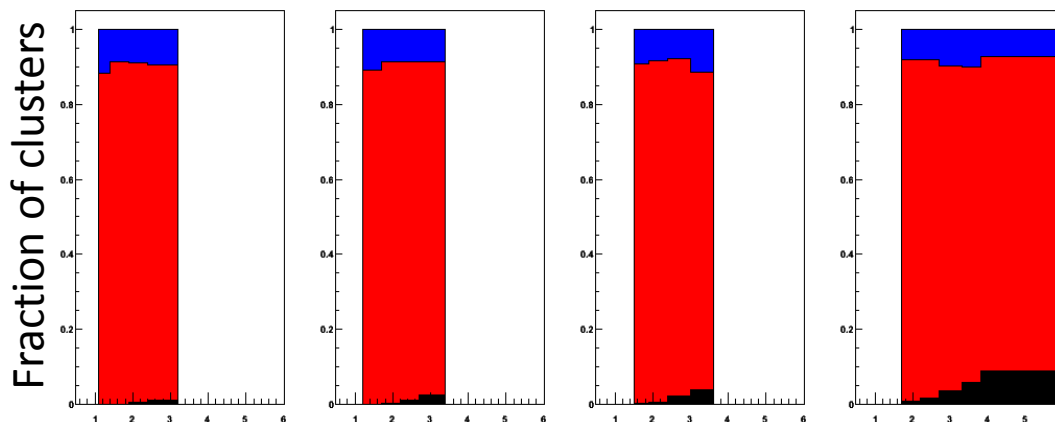
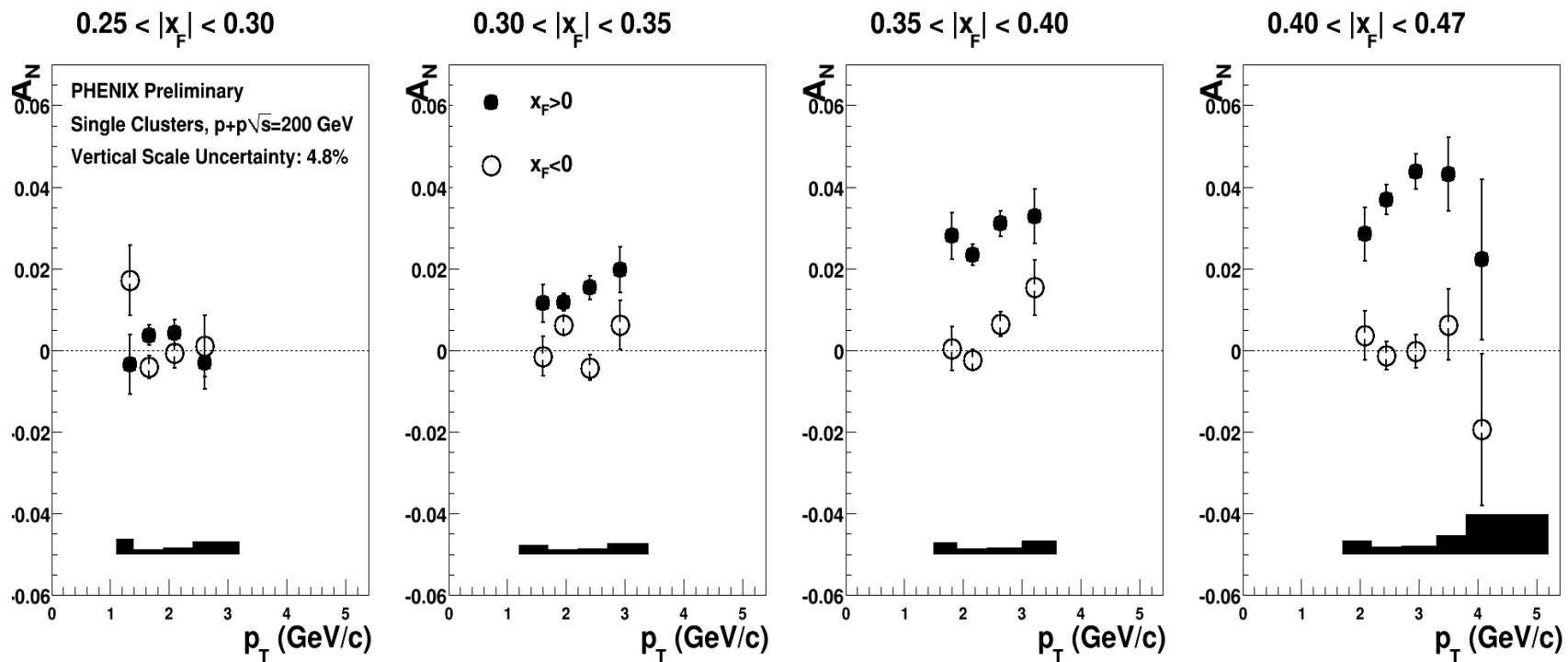
Forward A_N Cluster at $\sqrt{s}=200$ GeV



process contribution to π^0 ,
 $\eta=3.3$, $\sqrt{s}=200$ GeV



Forward A_N Cluster at $\sqrt{s}=200$ GeV

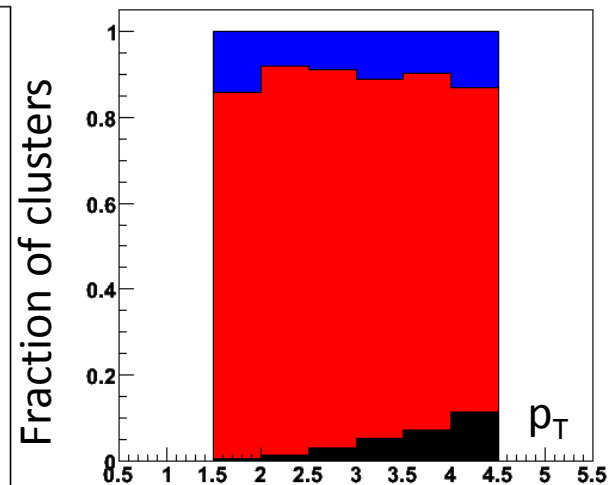
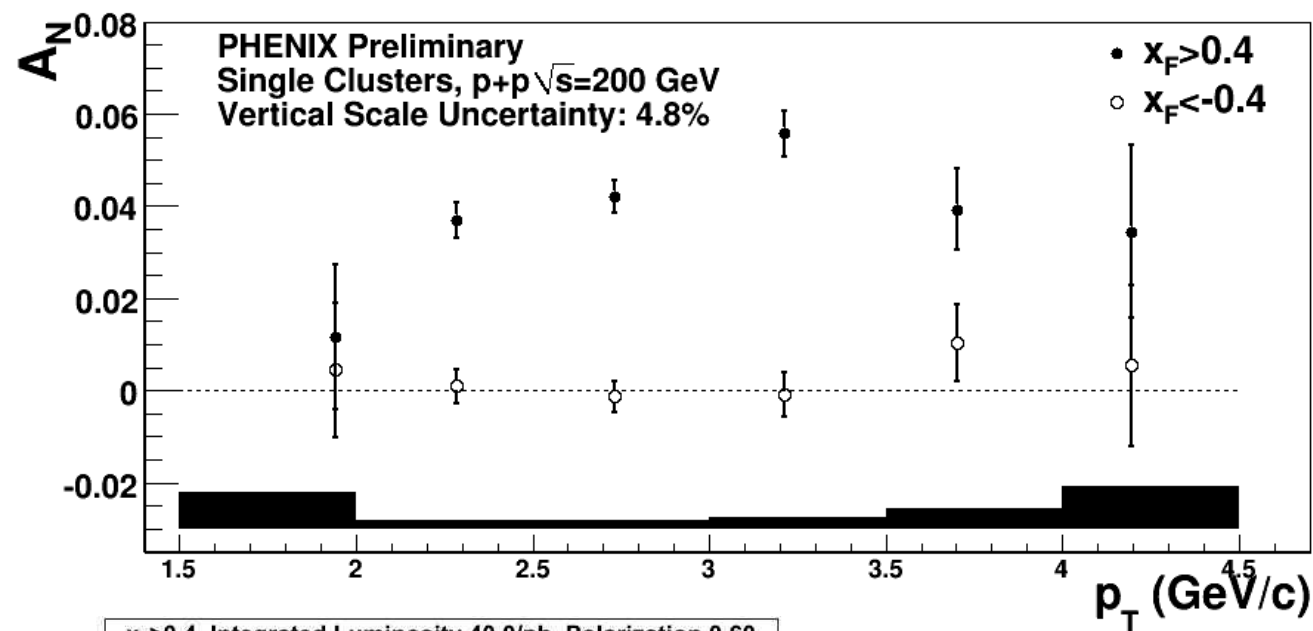


Decay photon

π^0

Direct photon

p_T Dependence



Decay photon

π^0

Direct photon

$x_F > 0.4$, Integrated Luminosity 40.0/pb, Polarization 0.60

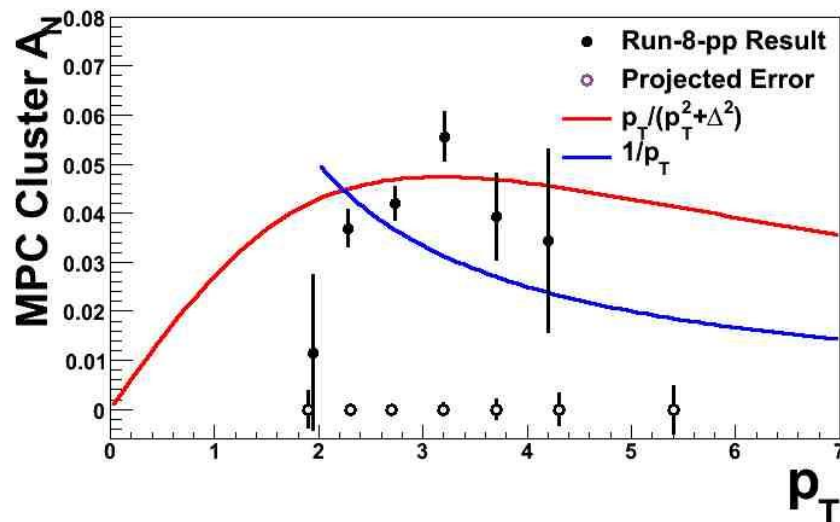


Figure of Merit:

This analysis: 1.1 pb^{-1}

Projected 2012+2013: $66. \text{ pb}^{-1}$

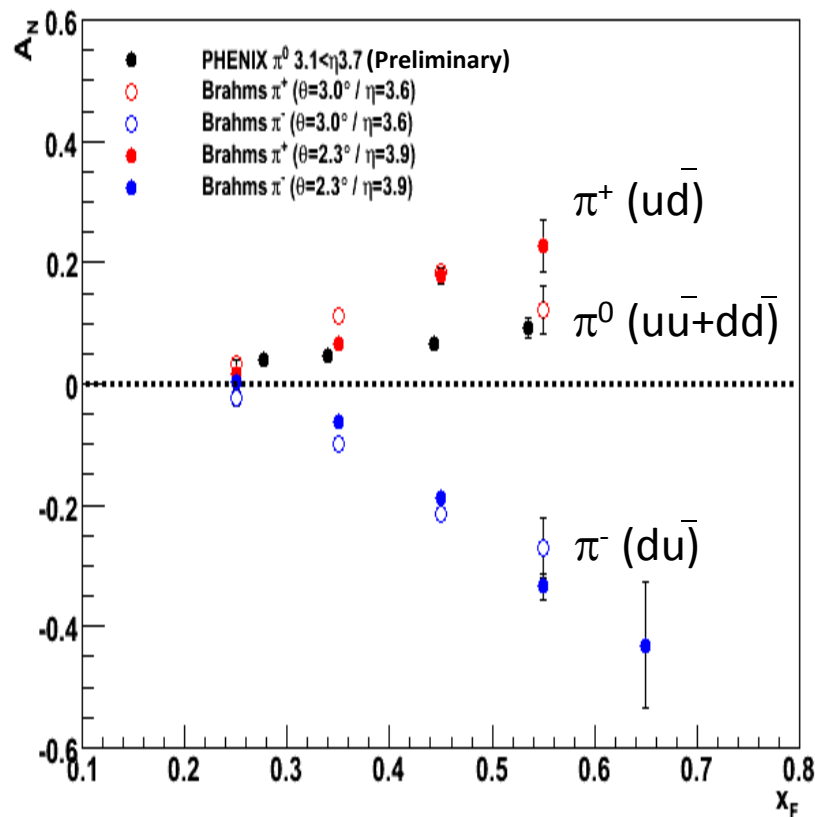
→ Errors shrink by factor of 8.

In addition, triggering system is being upgraded now.

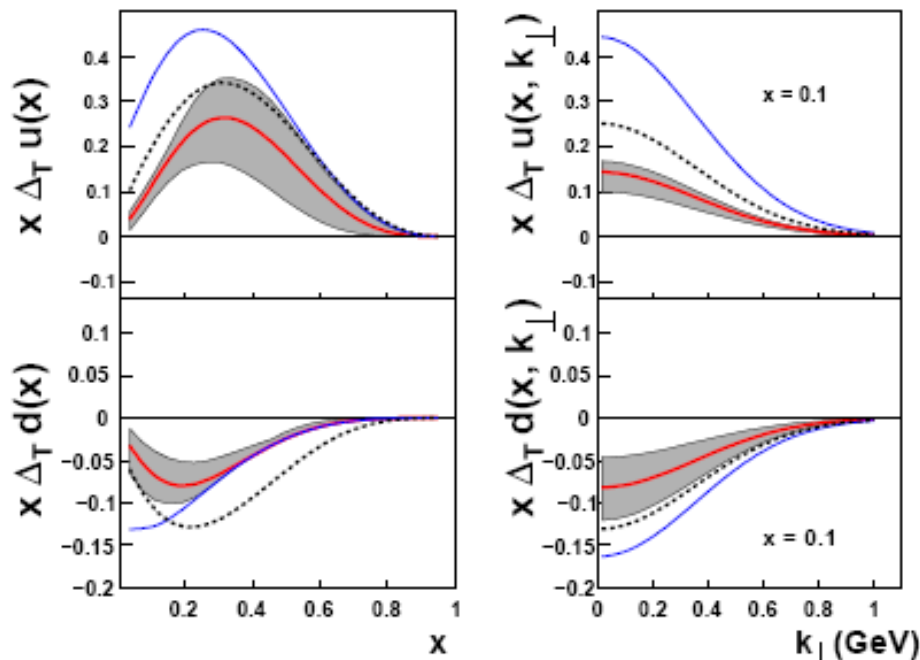
→ Greater efficiency



Isospin Dependence (“Collins”)



Transversity PDF

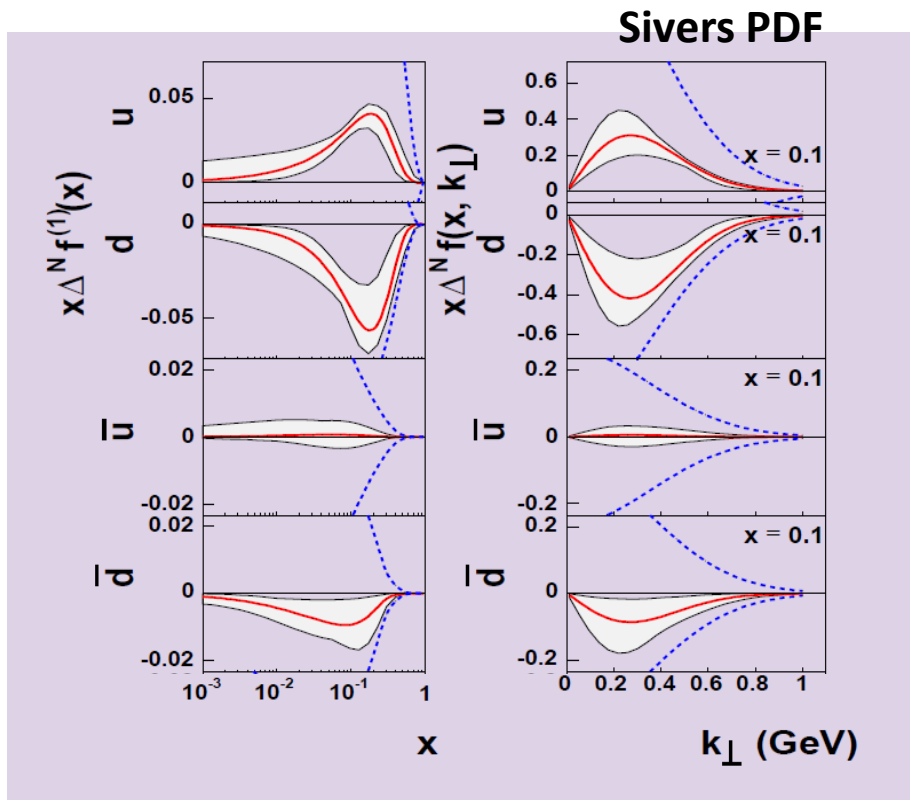
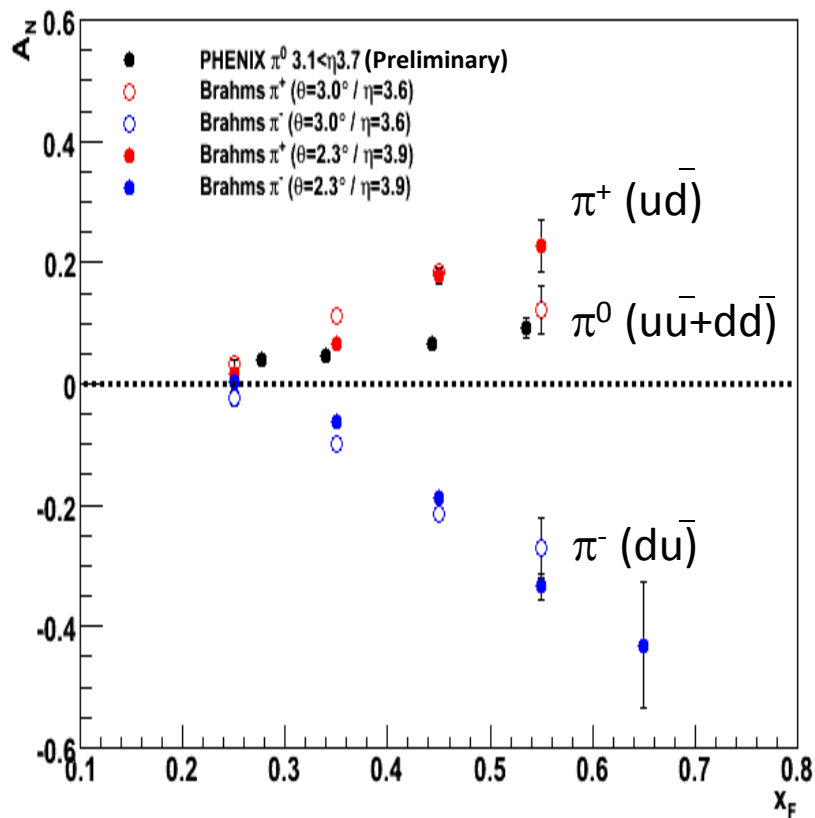


$$\delta q^a(x_a, k_T) \otimes f^b(x_b) \otimes \hat{\sigma}^{ab \rightarrow c} \otimes H_{1,c}^\perp$$

Transversity \otimes Collins:

- Sign of A_N seems consistent with sign of transversity
- However, transversity larger for u , but A_N is larger for π^+
 - Collins is symmetric between π^+ and π^- so it doesn't contribute to difference
- π^0 not average of π^+ and π^-
- What is π^0 Collins? Might be 0 (Belle's sees ¹⁷ isospin symmetry in π^\pm Collins)

Isospin Dependence (“Sivers”)

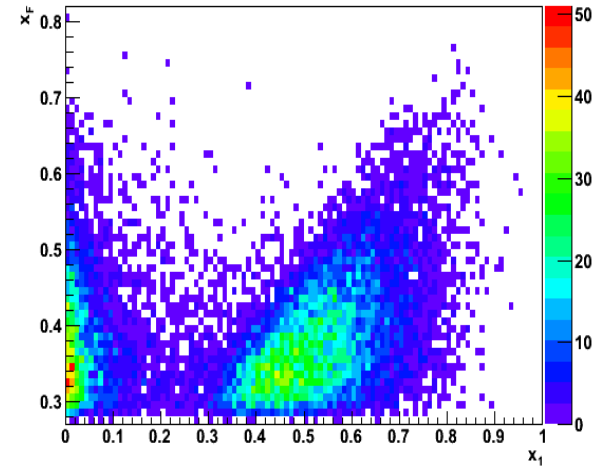
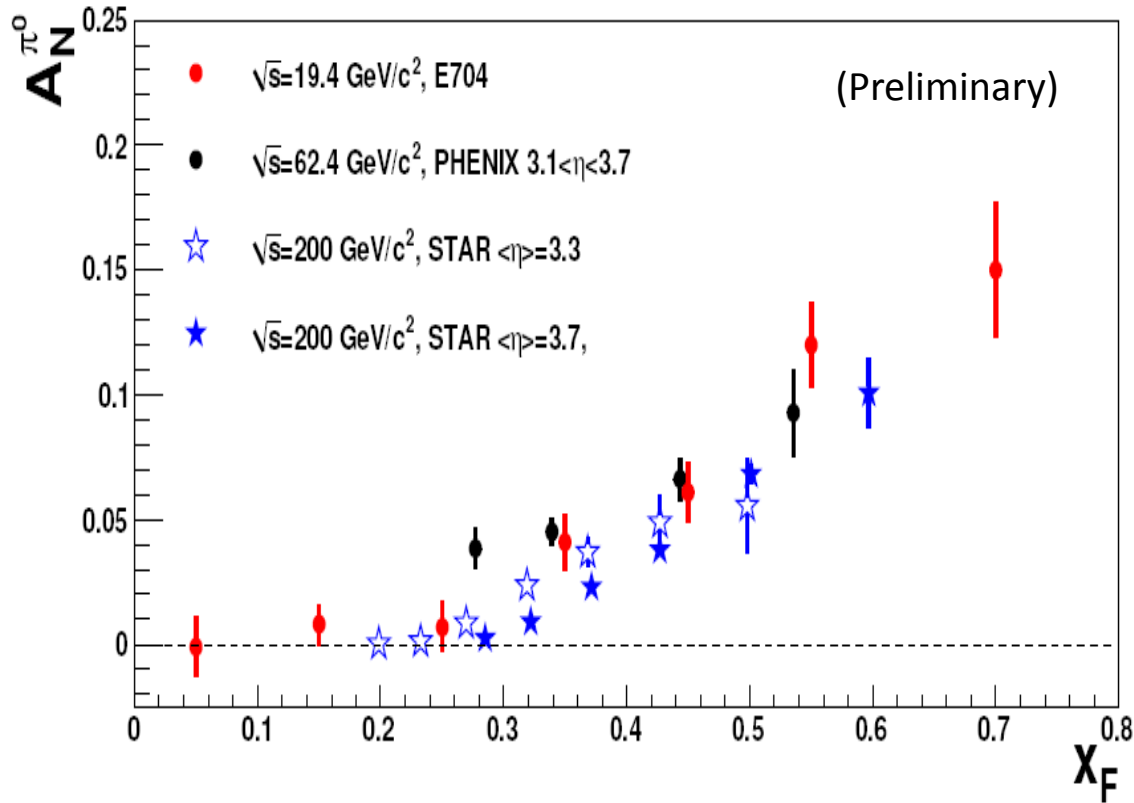


Sivers:

$$f_{q/p}^a(x_a, k_{T,a}) \otimes f_{q/p}^b(x_b) \otimes \hat{\sigma}^{ab \rightarrow c} \otimes D_c^h$$

- Sign also consistent with Sivers
- Again, Sivers larger for u, but A_N is larger for π^+ Maybe due to udbar? (opposite to u)
- Is $A_N(\pi^0) \sim 2A_N(\pi^+) + A_N(\pi^-)$???
- Factorization/Universality breaks down??? 18

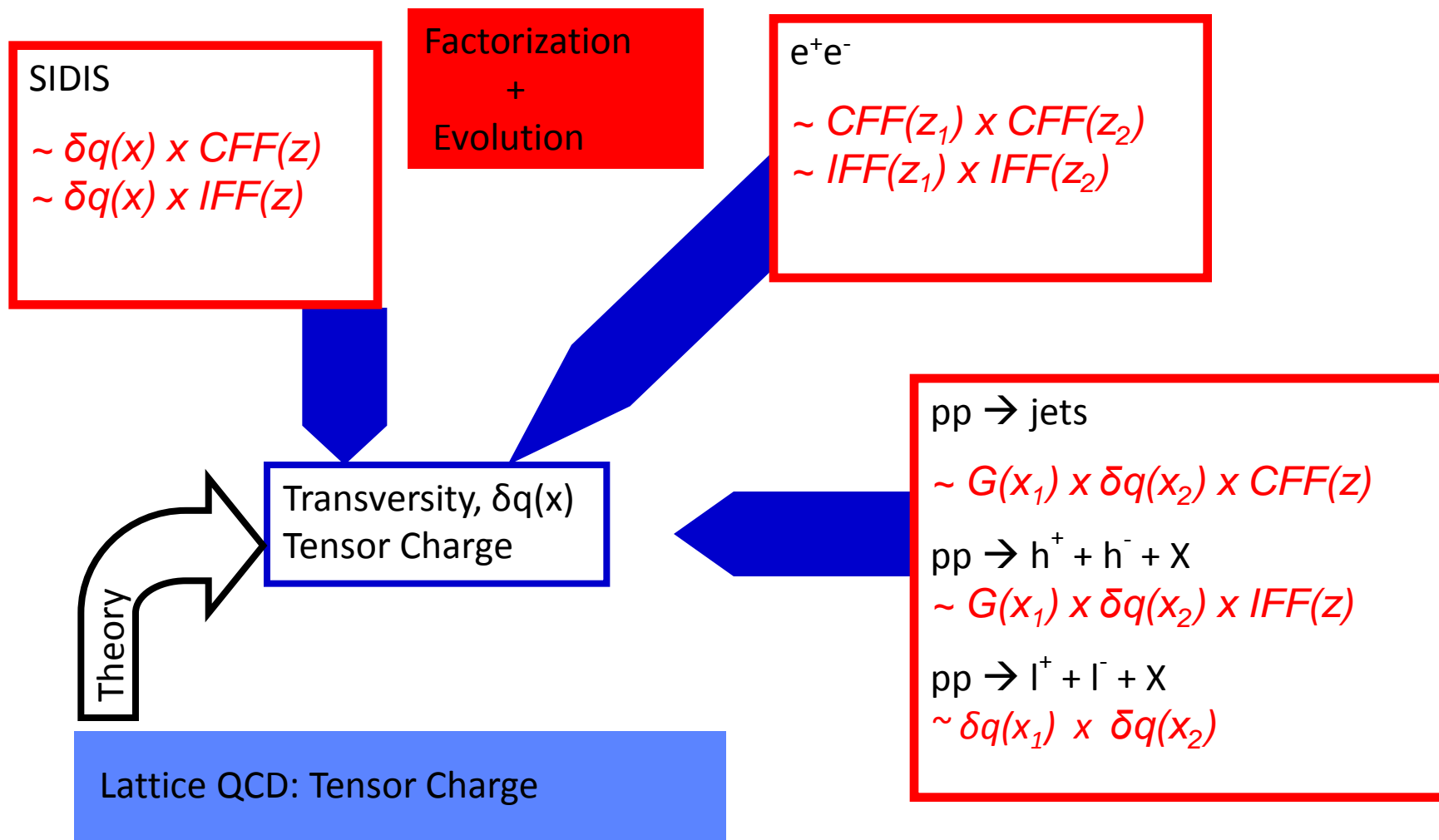
\sqrt{s} Dependence of $\pi^0 A_N$



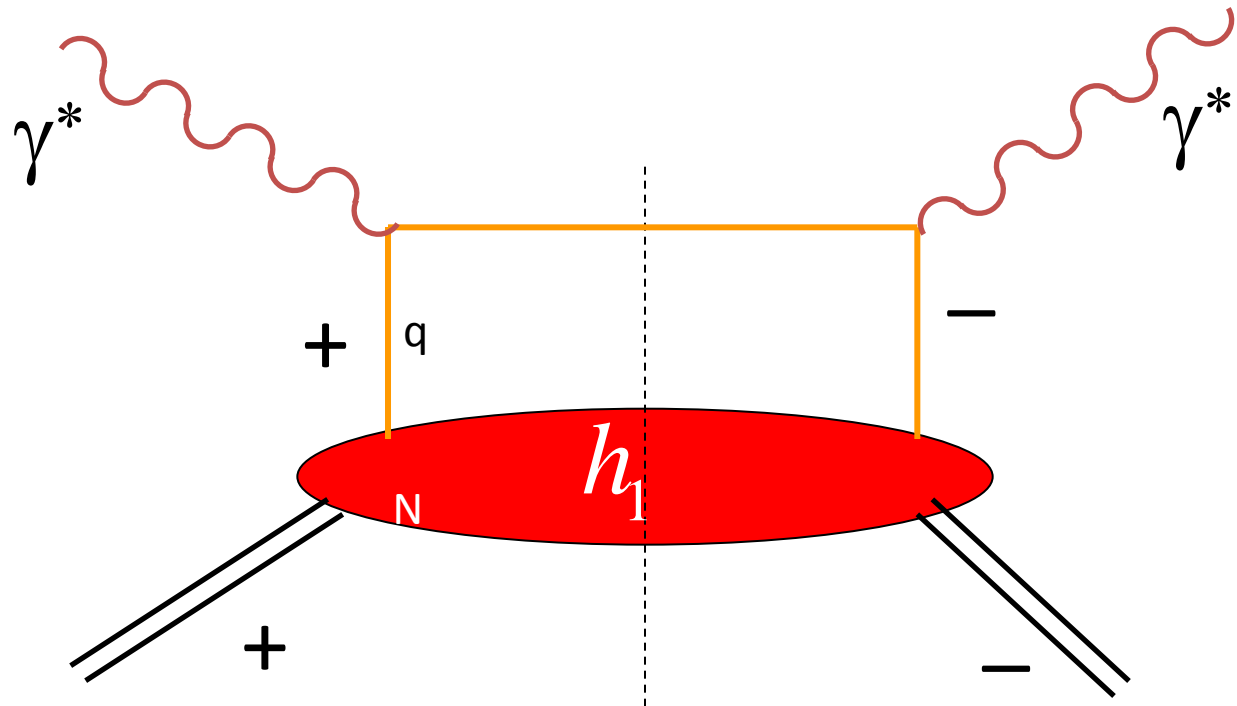
- No strong dependence on \sqrt{s} from 19.4 to 200 GeV
 - Spread probably due to different acceptance in pseudorapidity and/or p_T
- $x_F \sim \langle z \rangle P^{\text{jet}}/P_L \sim x$: shape induced by shape of Collins/Sivers (weak evolution)



Combined Analysis: Extract Transversity Distributions



Ψ Accessing Transversity with Chiral odd Fragmentation Functions

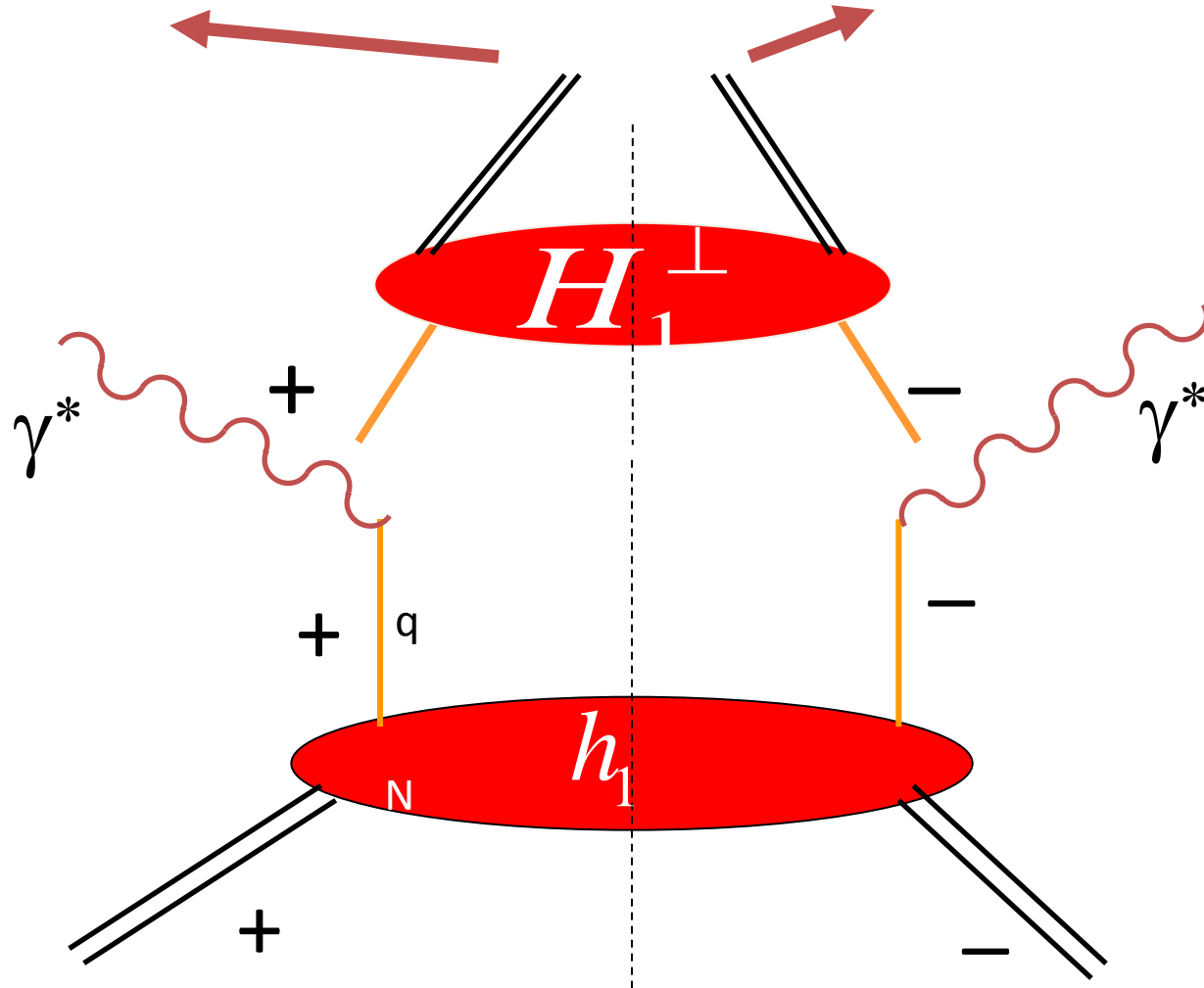


H_1^\perp : Collins FF

$+, -$: Helicity States

Ψ Accessing Transversity with Chiral odd Fragmentation Functions

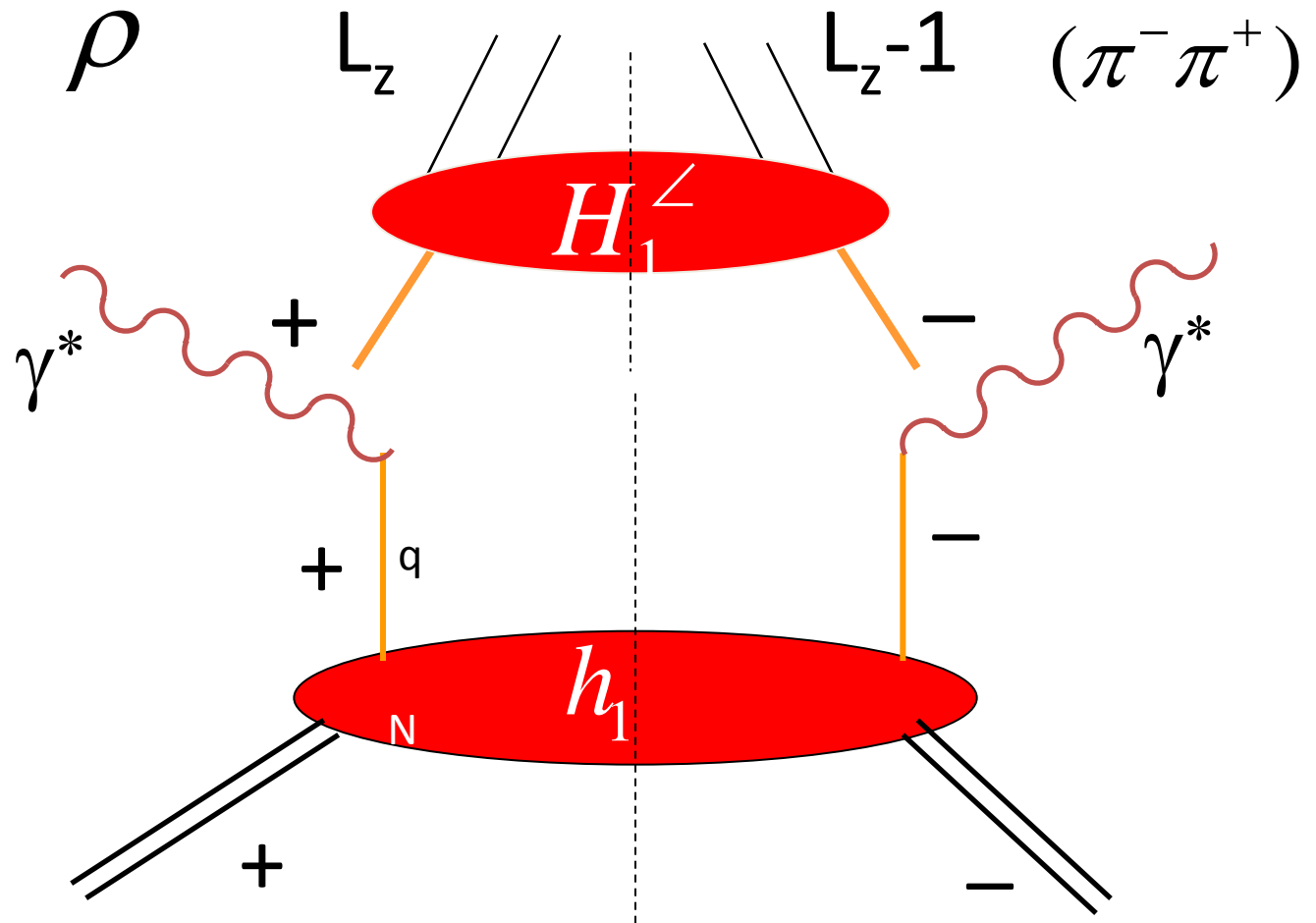
Collins effect



H_1^\perp : Collins FF

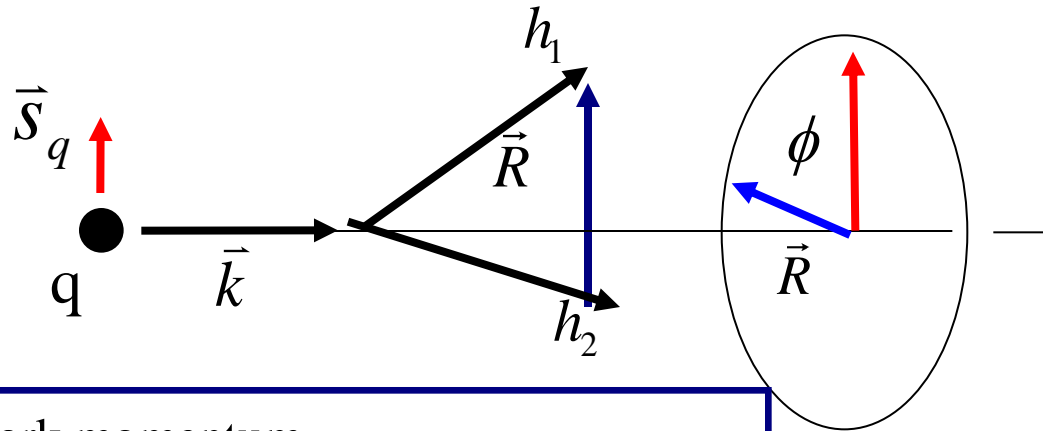
Chiral odd FFs

Interference Fragmentation Function





Interference FF in Quark Fragmentation



\vec{k} : quark momentum
 \vec{s}_q : quark spin
 \vec{R} : momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$
 \vec{R}_T : transverse hadron momentum difference
 $z_{\text{pair}} = E_{\text{pair}} / E_q$
 $= 2 E_{\text{pair}} / \sqrt{s}$: relative hadron pair momentum

Interference Fragmentation Function:

Fragmentation of a transversely polarized quark q into two spin-less hadron $h1, h2$ carries an azimuthal dependence:

$$\propto (\vec{k} \times \vec{R}_T) \cdot \vec{s}_q$$

$$\propto \sin \phi$$



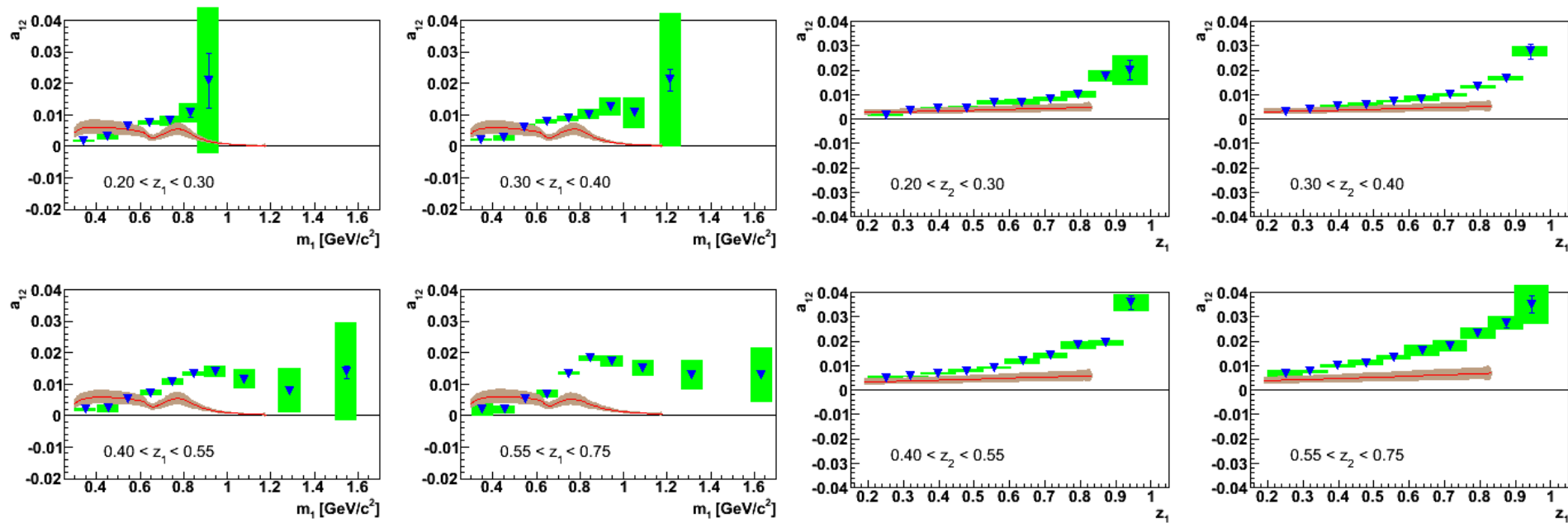
Advantages of IFF

- Independent from Collins Asymmetries
- Favorable in pp: no Sivers
- Transverse momentum is integrated
 - Collinear factorization
 - No assumption about k_t in evolution
 - evolution known, collinear scheme can be used
 - Universal function: directly applicable to semi-inclusive DIS and pp
- First experimental results from HERMES, COMPASS and now Belle

Good for PHENIX acceptance – no effect of jet axis reco.



Comparison to Theory Predictions



Initial model description by Bacchetta, Checcopieri, Mukherjee, Radici :
Phys.Rev.D79:034029,2009.

Leading order,

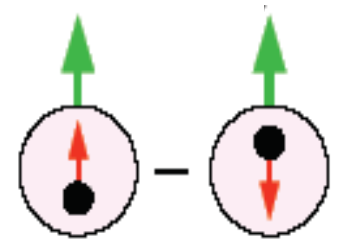
Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)

Z dependence : Rising behavior steeper

However: Theory contains parameters based on HERMES data which already fail to explain COMPASS well

Ψ Transversity $dq(x)$

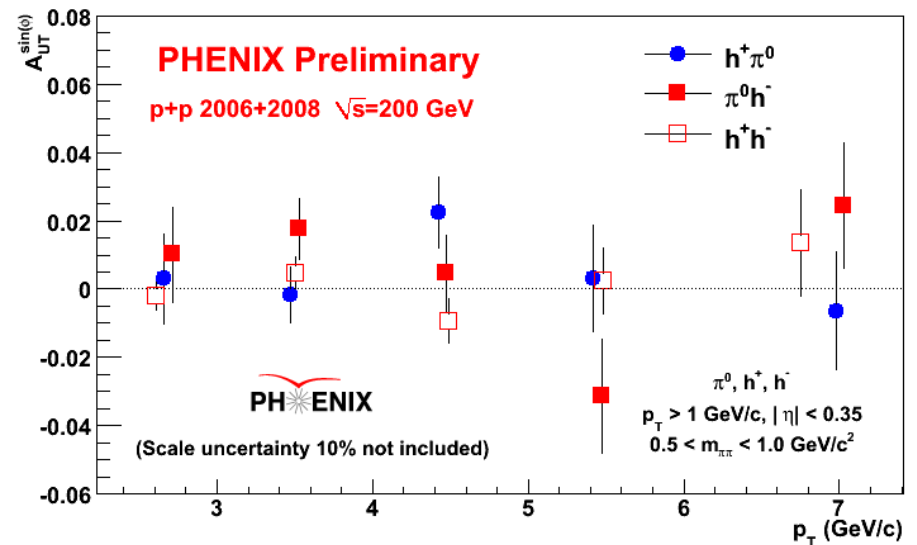
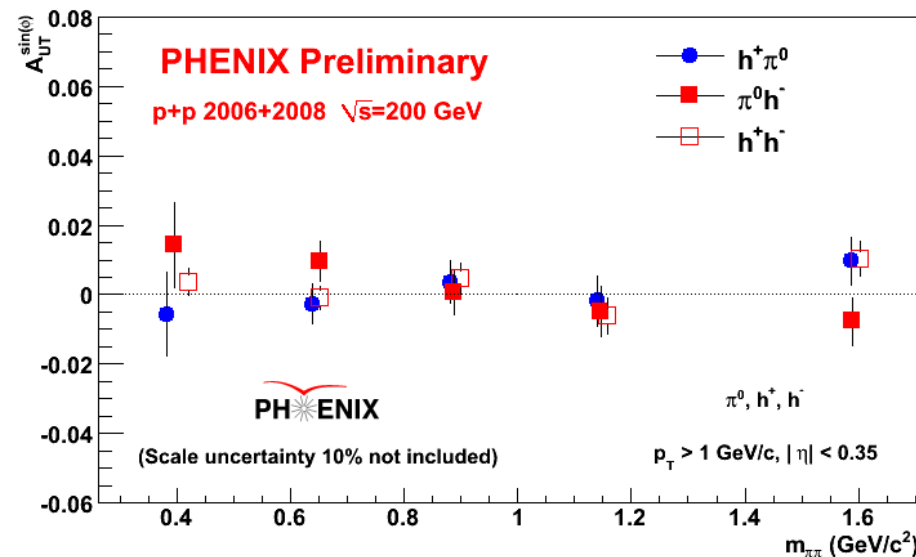
Transverse spin information at leading twist



$$A_{UT,\phi}^{h_1,h_2} = \frac{\sigma_{\phi}^{\uparrow} - \sigma_{\phi}^{\downarrow}}{\sigma_{\phi}^{\uparrow} + \sigma_{\phi}^{\downarrow}}$$

Measure $dq \times$ Interference
Fragmentation functions

Transversity extraction will become possible with Interference Fragmentation Function -
BELLE has shown first observation of IFF asymmetries



Exploring analysis with hadrons in forward region

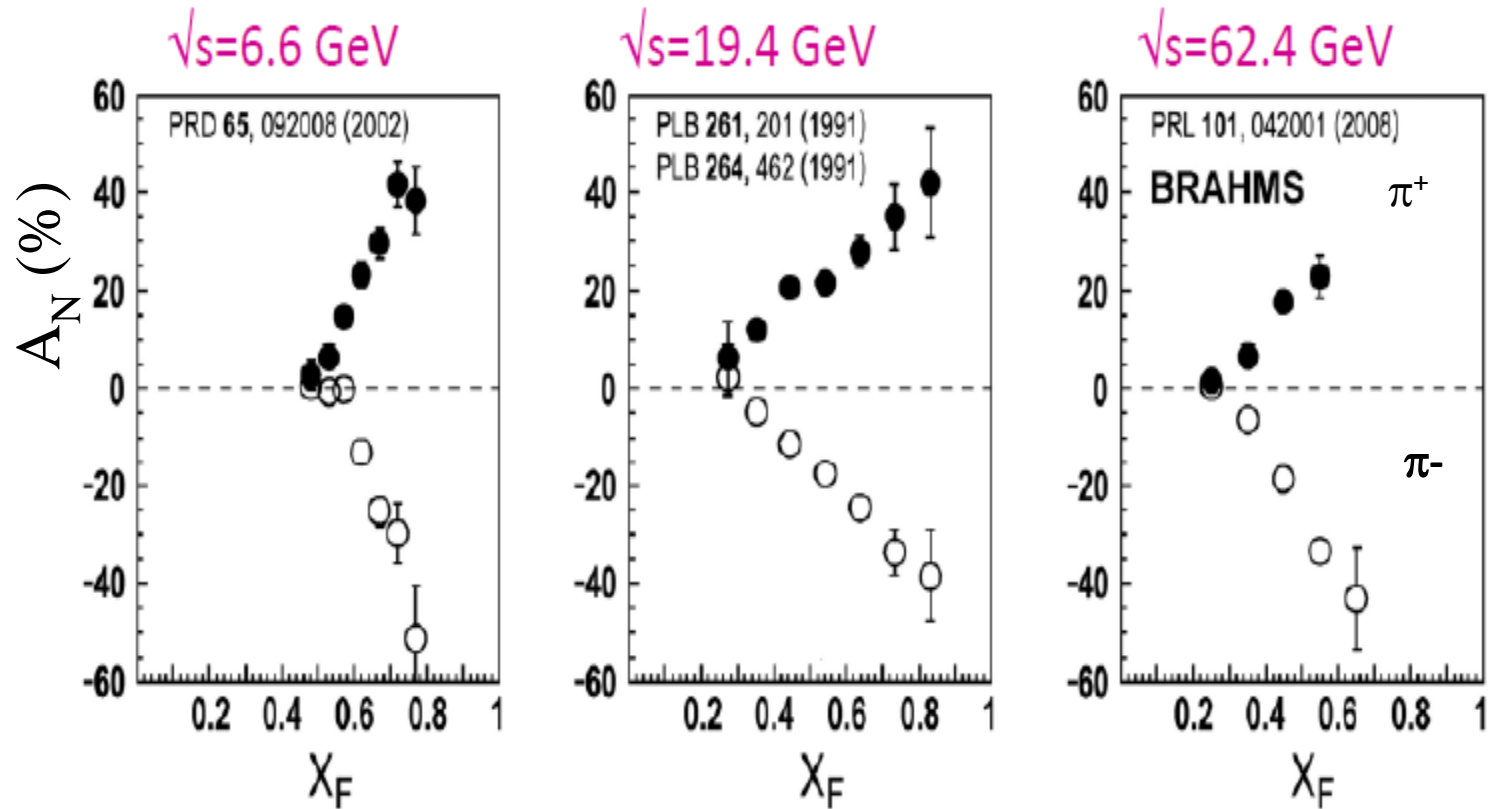


Summary

- Transverse polarization allows the measurement 'tensorial' quantities
- In leading collinear picture transversity needed to describe spin structure of the proton
- In non-collinear or non-leading twist picture: Access to new quantities
- Currently transverse single spin asymmetries at forward angles provide best way to test our knowledge of transverse spin physics in polarized pp collisions
- Di-hadron interference FF is promising way to disentangle transversity contribution
- Transverse spin effects can play a role in the search for parity violation in high energy pp collisions
- Outlook:
 - PHENIX is working at Eta asymmetries
 - AN and IFF will profit from higher integrated luminosity
 - Channels allowing to disentangle contributions to AN likely only accessible with forward upgrade: See talk by C. Aidala and Star talks
- Thanks to my colleagues at PHENIX, especially at UIUC and the PPG for the forward A_N
 - John Koster
 - Matthias Grosse Perdekamp
 - Mickey Chiu
 - Oleg Eyser
 - Chris Pinkenburg
 - Sasha Bazilevsky

Backup Slides

\sqrt{s} Dependence of $\pi^\pm A_N$



•Features:

- $\pi^\pm A_N(x_F)$ are opposite in sign and symmetric in magnitude until $\sqrt{s} = 62.4$ GeV
- x_F intercept (where $x_F \rightarrow 0$) seems to saturate at ~ 0.2 , but is ~ 0.5 at $\sqrt{s} = 6.6$ GeV
- Maximum measured asymmetry the same (accident of where statistics runs out?)

Transverse Proton Spin Physics

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_Z^q + L_Z^g$$

$$\begin{aligned}\Delta q &= q_+ - q_- \\ \Delta G &= g_+ - g_- \\ \Delta_T q &= q_\uparrow - q_\downarrow\end{aligned}$$

Polarized parton distribution functions

quark helicity distribution – known

gluon helicity distribution – poorly known

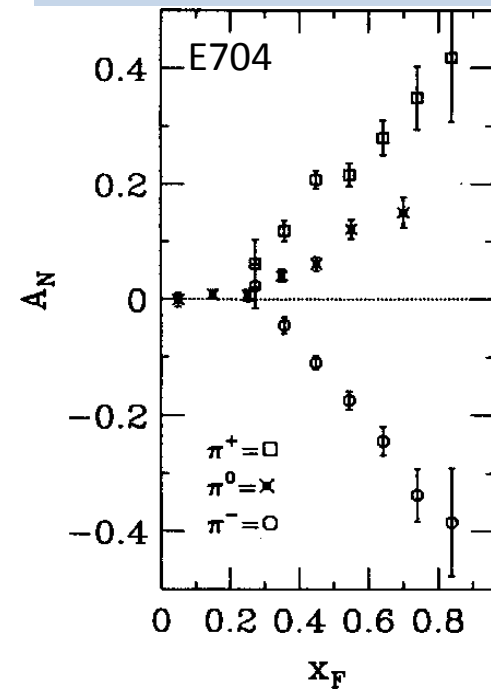
transversity distribution – unknown

Naïve LO, Leading Twist, pQCD Result

In this note we have pointed out that the asymmetry off a polarized target, and the transverse polarization of a produced quark in $e^+e^- \rightarrow q\bar{q}$, or in $qq \rightarrow qq$ at large p_T , or in leptonproduction, should all be calculable perturbatively in QCD. The result is zero for $m_q=0$ and is numerically small if we calculate m_q/\sqrt{s} corrections for light quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large- p_T production [where currently $P(\Lambda)=25\%$ for $p_T \approx 2 \text{ GeV}/c$], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

Kane, Pumpkin and Repko PRL 41 1978

$pp \rightarrow \pi X$ at $\sqrt{s} = 19.4 \text{ GeV}$



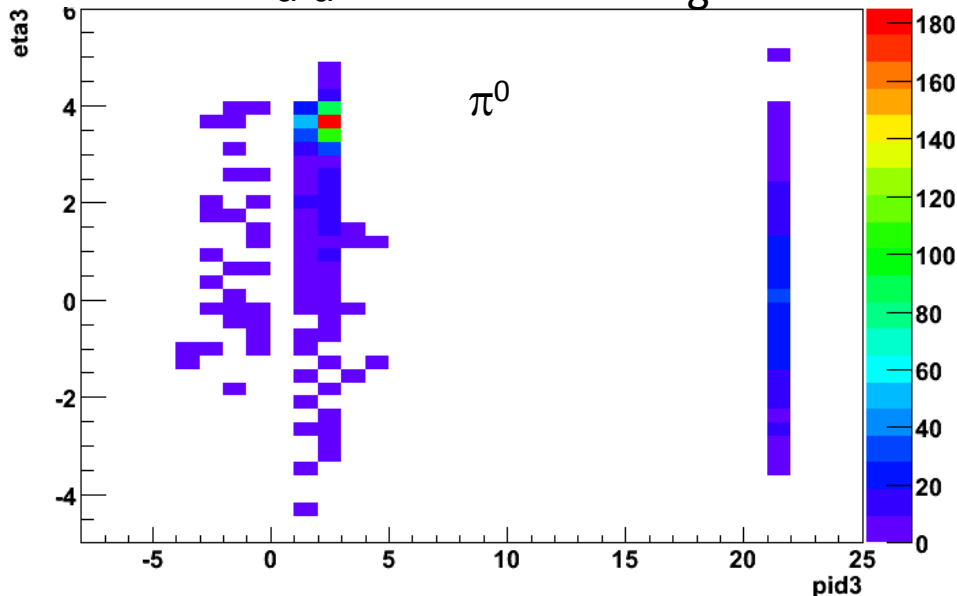
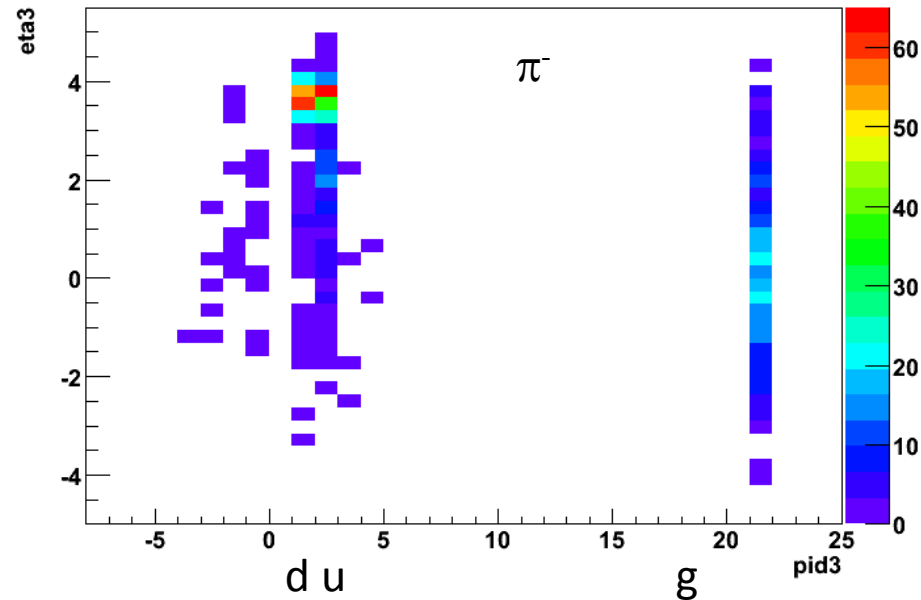
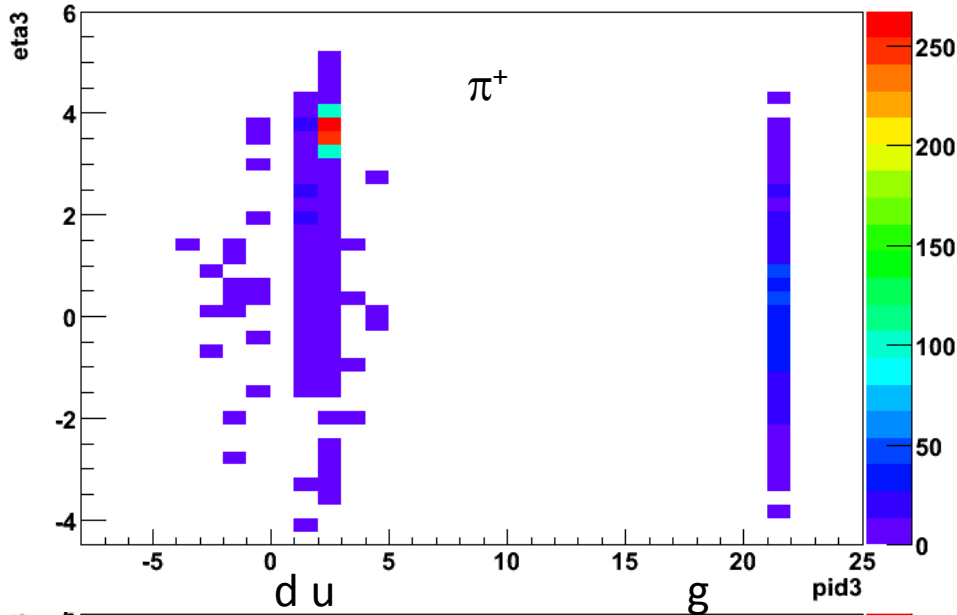
$$A_N \propto \frac{m_q}{\sqrt{s}} \text{ example, } m_q = 3 \text{ MeV}, \sqrt{s} = 20 \text{ GeV}, A_N \approx 10^{-4}$$

Helicity violation term due to finite quark masses

RVTLHA C 2.1.4 Studies Overview

eta3:pid3 {pzh>40&&pth>1&&pidh==211}

eta3:pid3 {pzh>40&&pth>1&&pidh==-211}

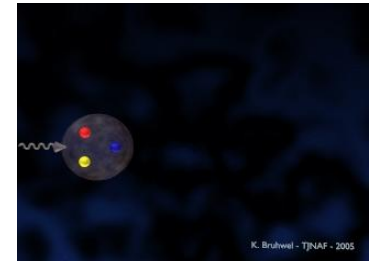


- TuneA, CKIN(3)=2, describes π^0 x-section well
- Extrapolation from known Sivers or Transversity/Collins depends on $\langle z \rangle$ and x versus \sqrt{s}
- Want to know outgoing jet type (Collins)
 - Same as incoming (Sivers)
- Soft vs Hard: @pT = 1 GeV, ~50/50
@pT = 2 GeV, ~90%
- π^+ : ~100%u, π^- : 50/50 d/u, π^0 : 25/75 d/u

Transverse Proton Spin Physics

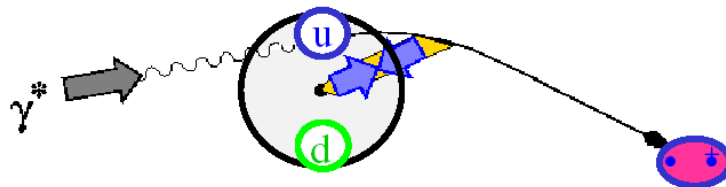
- Various possible explanations have been proposed to explain these asymmetries
 - Transversity x Spin-dep fragmentation (e.g., Collins effect or IFF),

$$D_{h/q^\uparrow}(z, \vec{p}_\perp) = D_{h/q}(z, p_\perp) + \frac{1}{2} \Delta^N D_{h/q^\uparrow}(z, p_\perp) \vec{S}_q \cdot (\hat{p}_q \times \hat{p}_\perp)$$



- Intrinsic- k_T in proton (Transverse Momentum Dep Functions) ,
 - Eg, Sivers Function

$$f_{q/p^\uparrow}(x, \mathbf{k}_\perp) = f_{q/p}(x, k_\perp) + \frac{1}{2} \Delta^N f_{q/p^\uparrow}(x, k_\perp) \mathbf{S}_T \cdot (\hat{\mathbf{P}} \times \hat{\mathbf{k}}_\perp)$$

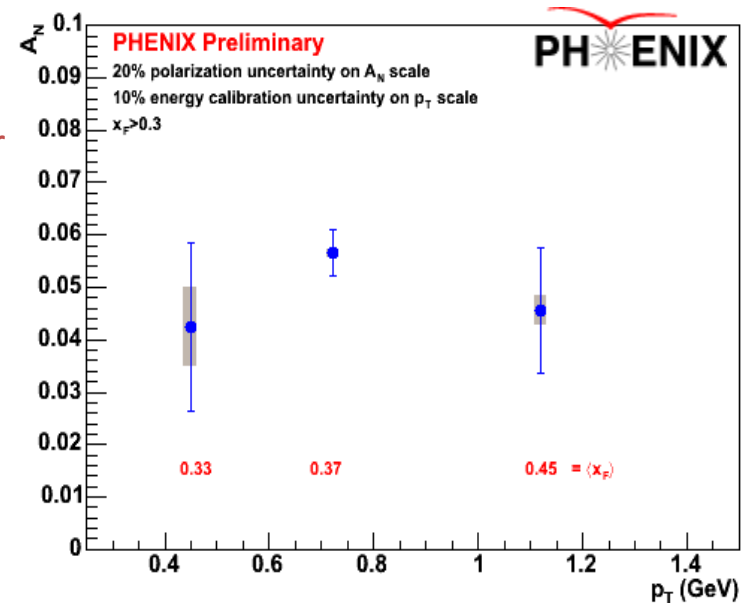
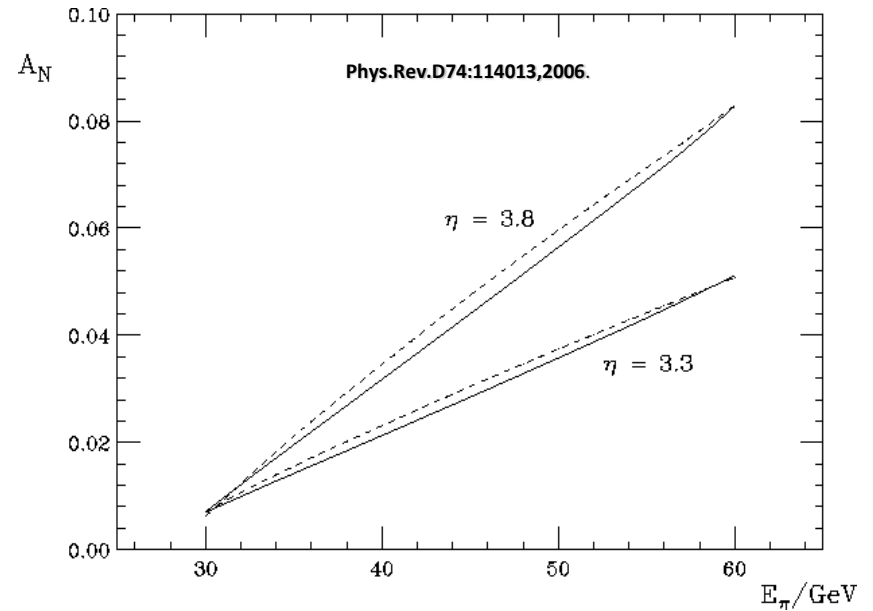
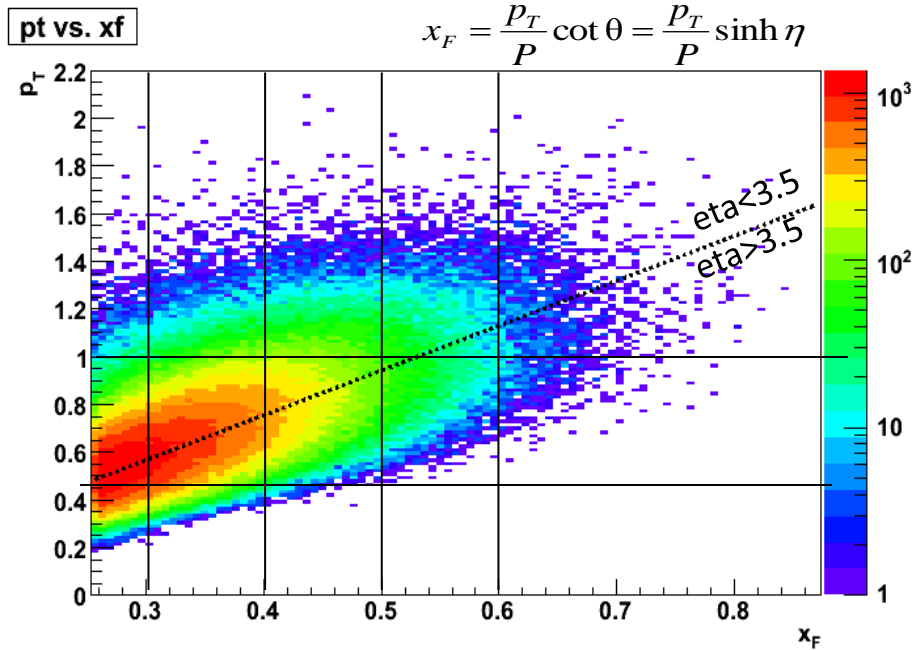


- Perturbative LO Twist-3 Calculations (Qiu-Sterman, Efremov, Koike)
 - These calculations have been related to the Sivers function

A Unified picture for single transverse-spin asymmetries in hard processes,
 Ji, Qiu, Vogelsang, Yuan **PRL97**:082002,2006

- Or some combination of the above
 - Caveat: The theory is still being actively worked out

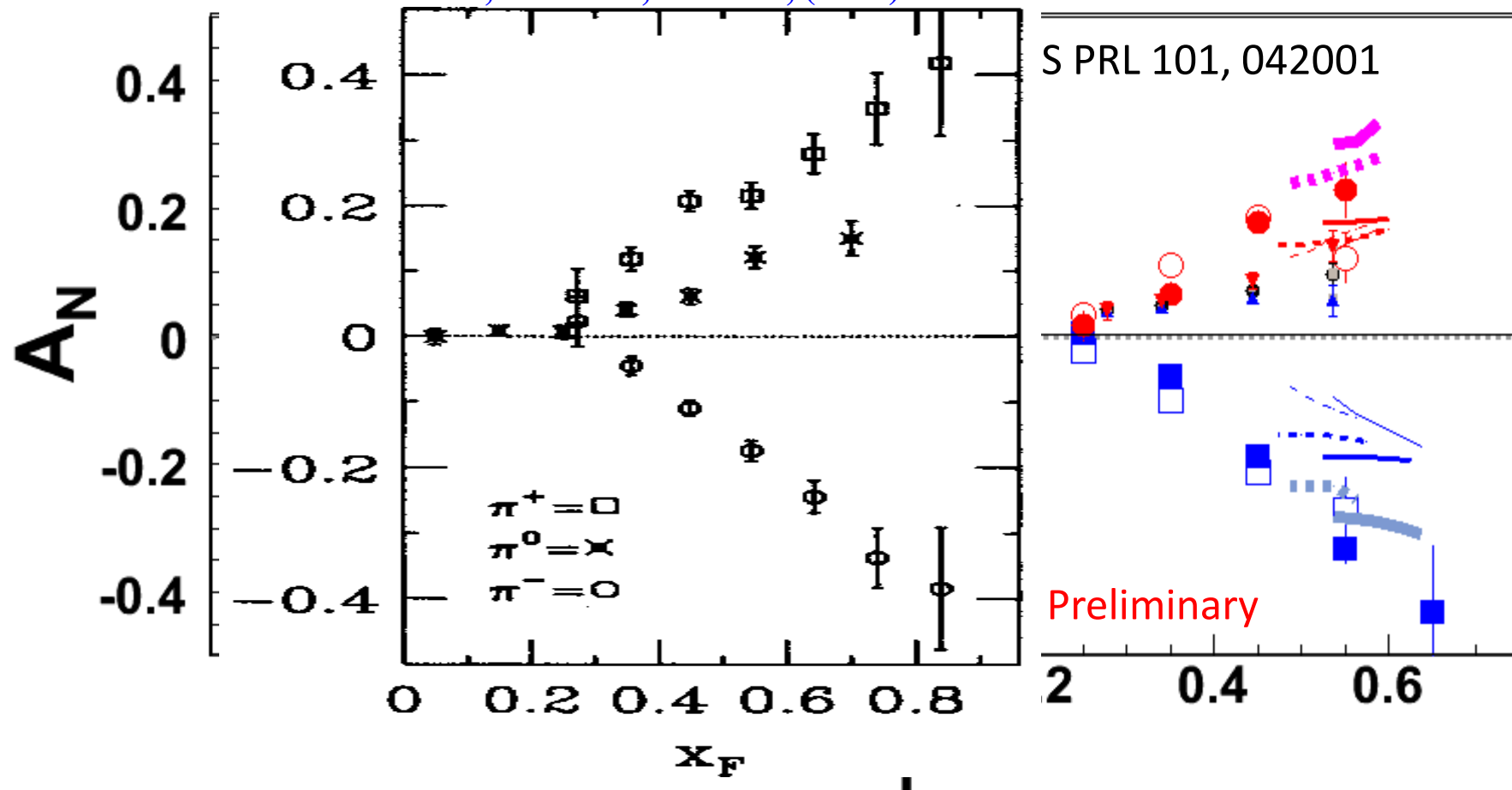
Kinematic Cuts and A_N



- Mean A_N is measured to be lower for $p_T > 1$, even though mean x_F is higher for this p_T bin, and higher x_F implies higher asymmetry
 - This implies that A_N is dropping with p_T for a given x_F slice
- The η cut, for a given x_F slice, splits that slice into high p_T and low p_T , with the lower η selecting higher p_T
 - This implies that A_N at lower η should be smaller, consistent with predictions of PRD74:114013
- However, at 62.4 GeV the p_T are low (pQCD invalid?)
 - Cross-section is being analyzed now

RHIC Forward Pion A_N at 62.4 GeV

E704, 19.4 GeV, PLB261, (1991) 201



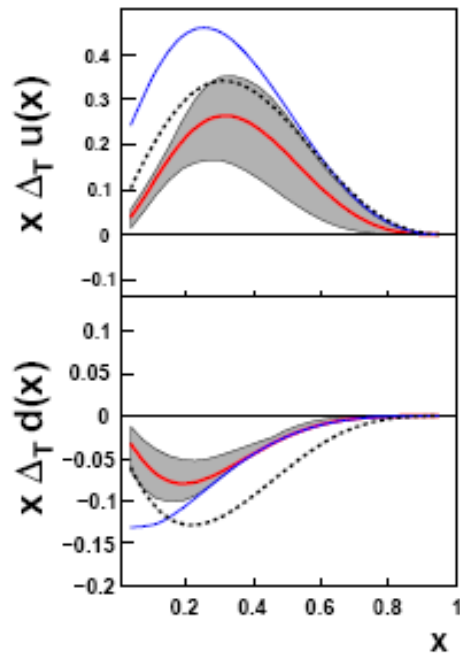
- Brahm's Spectrometer at "2.3°" and "3.0°" setting $\rightarrow \langle \eta \rangle = 3.44$, comparable to PHENIX all η
 - Qualitatively similar behavior to E704 data: π^0 is positive and between π^+ and π^- , and roughly similar magnitude: $A_N(\pi^+)/A_N(\pi^0) \sim 25\text{-}50\%$
 - Flavor dependence of identified pion asymmetries can help to distinguish between effects
- Kouvaris, Qiu, Vogelsang, Yuan, PRD74:114013, 2006
 - Twist-3 calculation for pions for pion η exactly at 3.3
 - Derived from fits to E704 data at $\sqrt{s}=19.4$ GeV and then extrapolated to 62.4 and 200 GeV

Carry Out Steps Analogous to QCD Analysis of Unpolarized Distributions (ii)

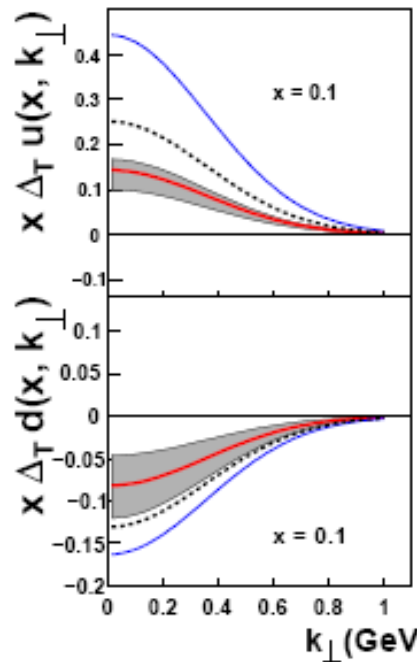
Extract Distributions from SIDIS and e^+e^-

Predict proton-proton observables

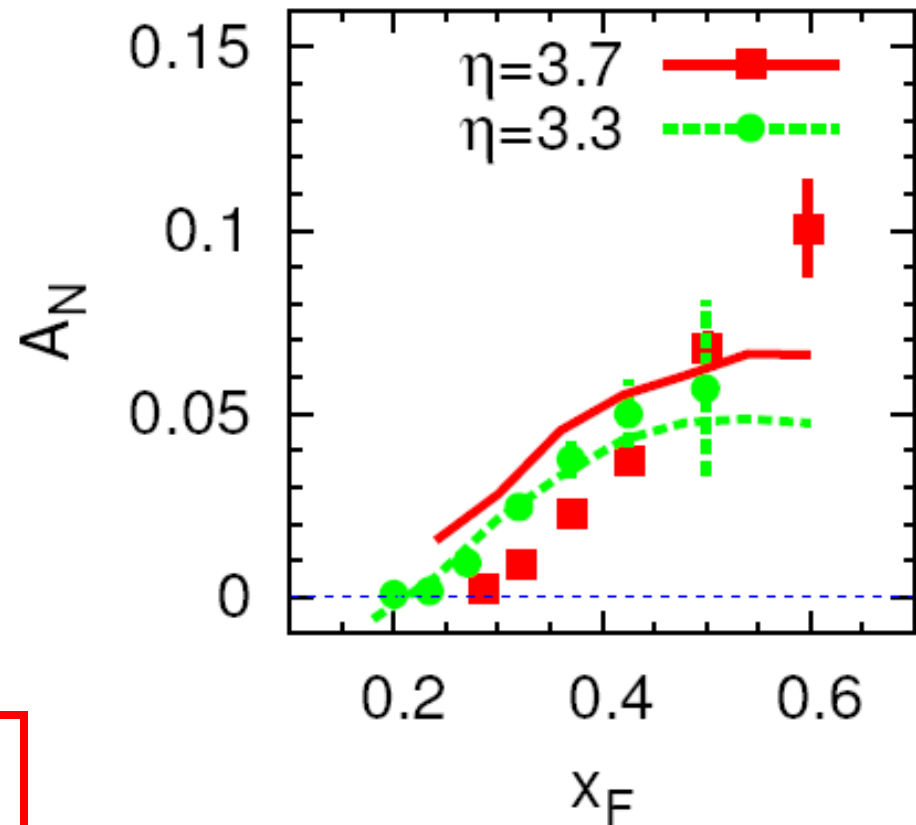
Transversity PDF



Sivers PDF

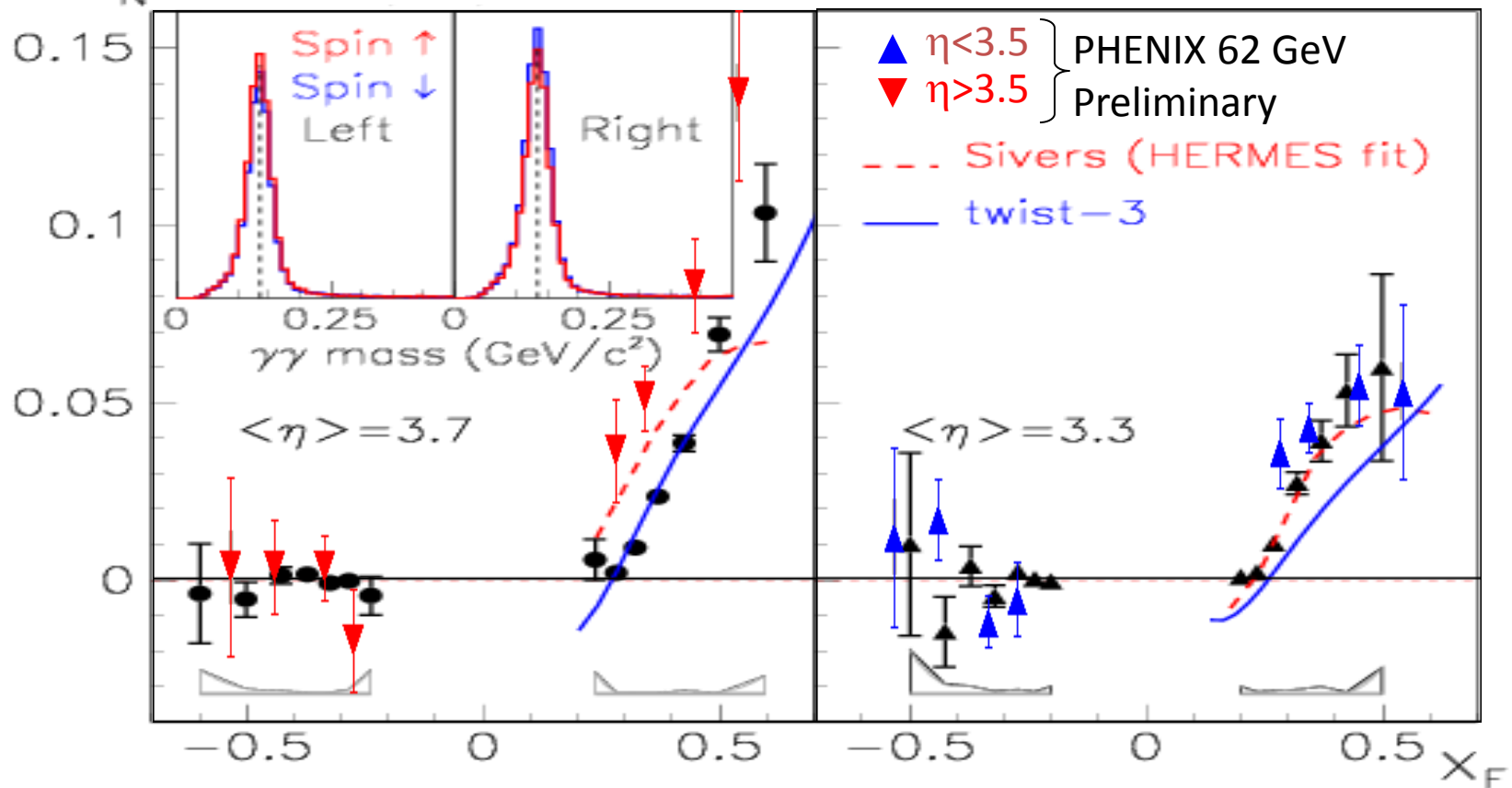


Disagreement between theory and experiment.



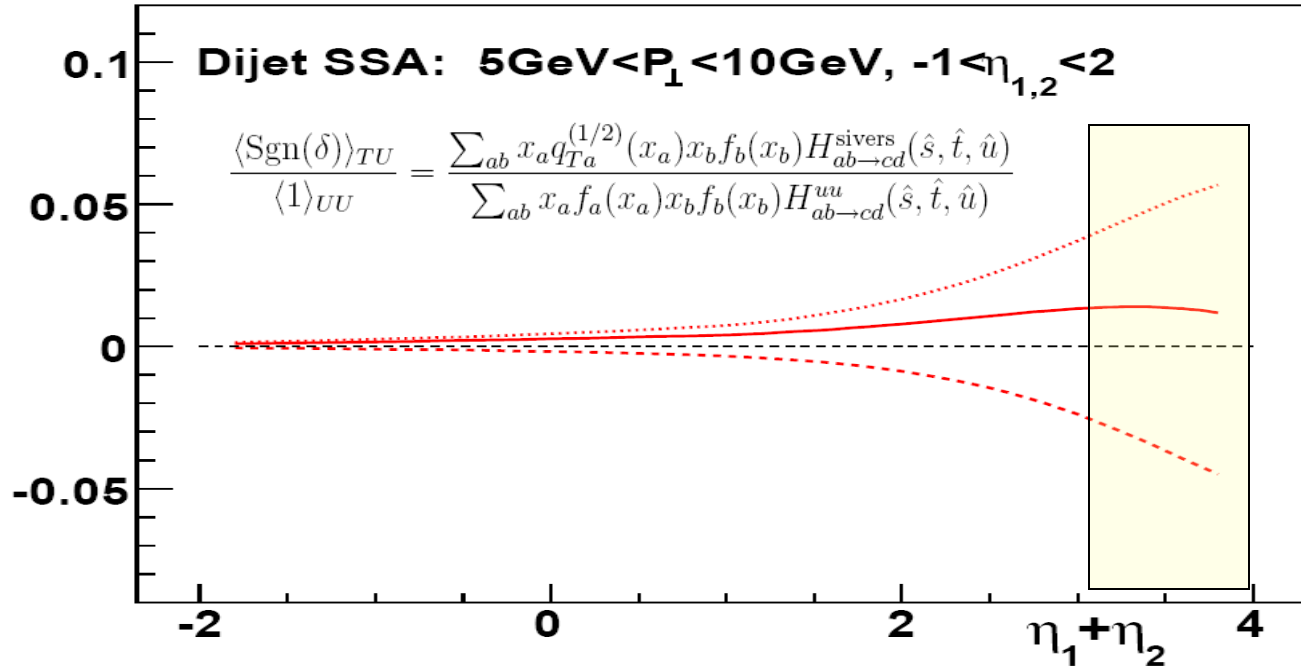
Comparison to π^0 at $\sqrt{s} = 200 \text{ GeV}/c^2$

STAR arxiv:0801.2990v1, $p+p \rightarrow \pi^0$ @ $\sqrt{s}=200 \text{ GeV}$, accepted by PRL



- At higher η , the scaling with \sqrt{s} is stronger?
- The η dependence is switched when going from 62 to 200 GeV?

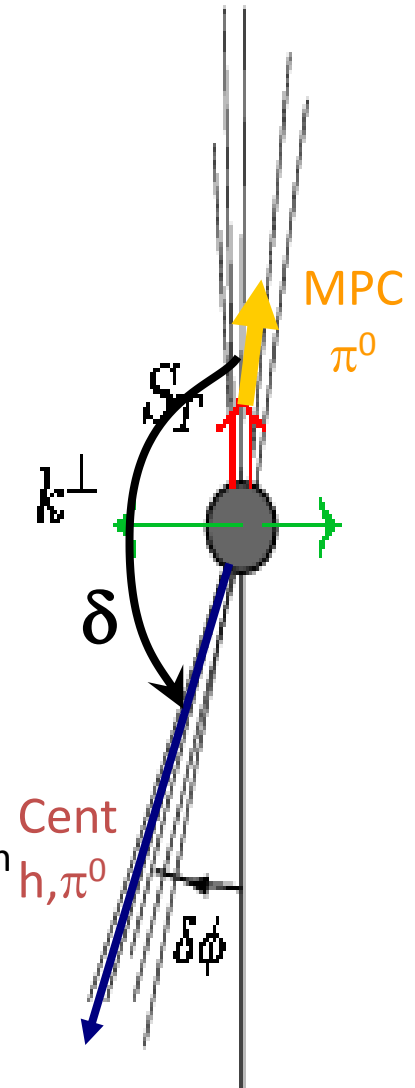
Sivers f_n from Back2Back Analysis



Boer and Vogelsang, Phys.Rev.D69:094025,2004, hep-ph/0312320

Bomhof,Mulders,Vogelsang,Yuan, PRD75:074019,2007

- Boer and Vogelsang find that this parton asymmetry will lead to an asymmetry in the $\delta\phi$ distribution of back-to-back jets
- Should also be able to see this effect with fragments of jets, and not just with fully reconstructed jets
- Important analysis to decouple the effects in single inclusive A_N



Particle Fractions of Single Clusters

1. Gene

Pick F
sectic

2. Propa
respo

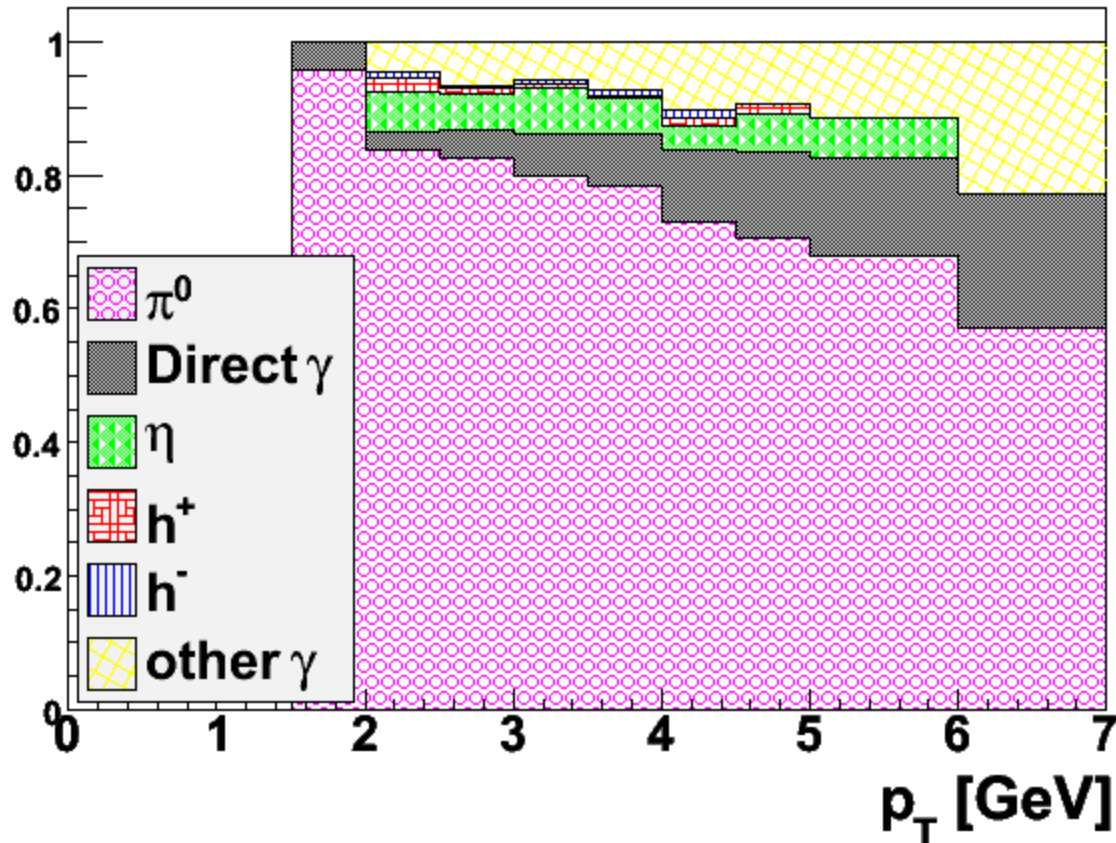
3. Prodi

4. Contr

— El

— H

Fraction



SS-

or

aring

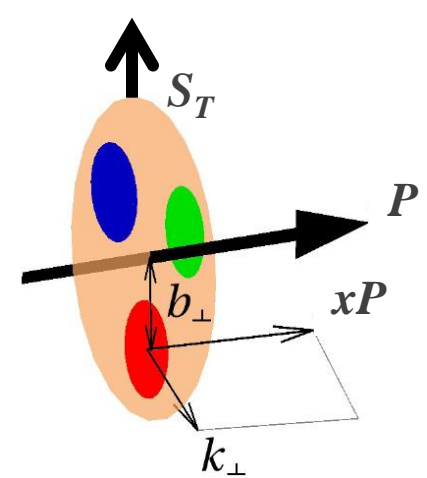
Ψ Mechanisms in QCD

I. Transverse momentum dependent (TMD) functions approach Sivvers function, Collins function ...

II. Collinear factorization approach

At high transverse momenta : two twist-3 correlation functions

1. Quark-gluon correlation function $T_{q,F}$
2. Two independent trigluon correlation functions $T_G^{(f)}, T_G^{(d)}$

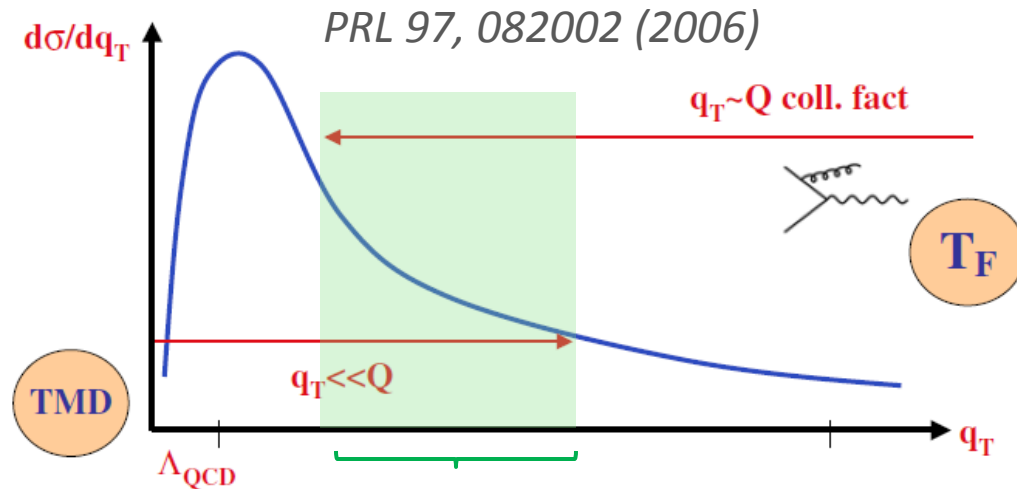


k_{\perp} is integrated



represent integrated spin dependence of the partons transverse motion

Are the two mechanisms related?



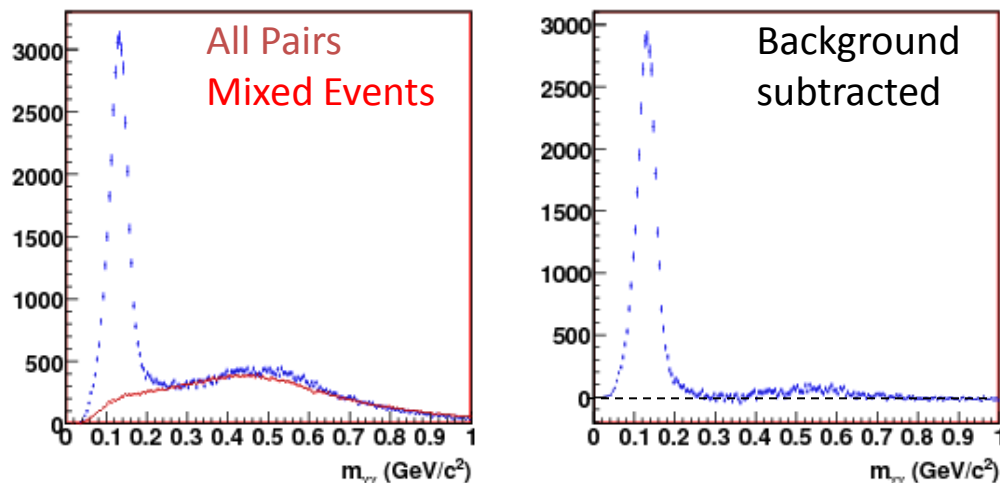
• $T_{q,F}, T_G^{(f)}$ related to a moment in k_{\perp} of the corresponding quark/gluon Sivvers function

Case study : Drell-Yan

In the overlap region both approaches give the same answer/physics

Muon Piston Calorimeter Performance

• Shower Reconstruction Using Shower Shape Fits



• Photon Pair Cuts (pi0 62 GeV)

- Pair Energy > 8 GeV
- Asymmetry $|E_1 - E_2| / |E_1 + E_2| < 0.6$
- Noisy Towers in Run06 (up to 25% of MPC) were excluded

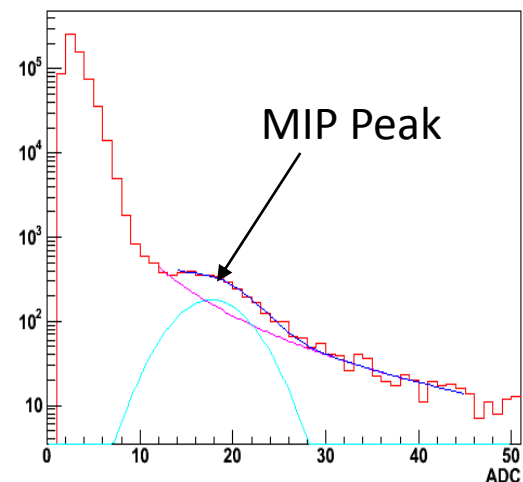
• Cluster Cuts (200 GeV)

- Energy > 25 GeV
- Fiducial Radial Cuts to avoid edges
- Only $\sim 4/416$ noisy towers excluded in Run08

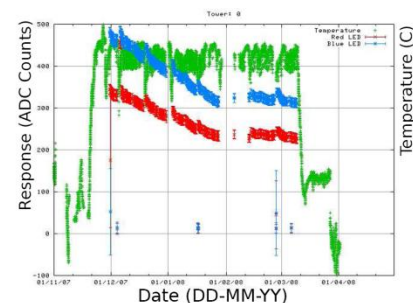
• Width ~ 20 MeV at 62.4 GeV, but improved by factor two in Run08 using pi0 tower by tower calibration ⁴¹

• 62.4 GeV Energy scale set by MIP

- In noisy towers, used tower spectrum



• LED Monitoring for gain stability



Transverse Single Spin Asymmetries

Definition:

$$A_N \equiv \frac{\sigma^\uparrow(p) - \sigma^\downarrow(p)}{\sigma^\uparrow(p) + \sigma^\downarrow(p)} = \frac{\Delta\sigma(p)}{\sigma(p)}$$

where p is the 4-momentum of a particle (hadron, jet, photon, etc...)

Experimentally, there are a variety of (~equivalent) ways this can be measured.

1. Yield difference between up/down proton in a single detector

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^\uparrow - R_{\text{lumi}} N^\downarrow}{N^\uparrow + R_{\text{lumi}} N^\downarrow} \quad R_{\text{lumi}} = L^+ / L^-$$

This is susceptible to Rel. Luminosity differences

2. Or, take the left-right difference between 2 detectors

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N_L^\uparrow - R_{\text{det}} N_R^\uparrow}{N_L^\uparrow + R_{\text{det}} N_R^\uparrow} = \frac{1}{P_{\text{beam}}} \frac{R_{\text{det}} N_R^\downarrow - N_L^\downarrow}{R_{\text{det}} N_R^\downarrow + N_L^\downarrow}$$

This is susceptible to detector Relative Acceptance differences

3. Or, take the cross geometric mean (square-root formula)

$$A_N = \frac{1}{P_{\text{beam}}} \frac{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} - \sqrt{N_L^\downarrow \cdot N_R^\uparrow}}{\sqrt{N_L^\uparrow \cdot N_R^\downarrow} + \sqrt{N_L^\downarrow \cdot N_R^\uparrow}}$$

Mostly insensitive to Relative Luminosity and Detector Acceptance differences

